Master Thesis, Department of Geosciences

Hydrogeological study of the Gvammsletta aquifers

Characterizing interconnections in a multiple aquifer system, Hjartdal, Norway

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Abstract

Unconsolidated sediments in intermountain valleys provide strategic groundwater reservoirs for cities and villages in Norway. These aquifers consist of alternating geological layers that present large variations in hydraulic conductivity leading to multiple confined aquifer systems. This study examines the differences in hydrogeological parameters and recharge sources of a two-layer system at Gvammsletta in Hjartdal municipality. A set of ten wells placed in pairs, in the upper and in the deeper aquifers, was monitored from 2011 until 2014. The recharge sources to the system are the precipitation, a lake contacting the eastern border of the aquifer, a river crossing from west to east, and a creek in the south. The upper aquifer is unconfined with a thickness that varies from 2 to 3 meters and is in contact with the lake in the east. The lower aquifer has an average thickness of 40 meters, is partially confined in the east with artesian water pressure and it is presenting hydraulic connection in the west with the upper part of the aquifer. An organic layer is dividing the upper aquifer from the lower aquifer. The extent of this layer is uncertain.

The data is statistically analyzed, in order to get a better understanding of the relation between the hydrological parameters. The analyses is showing a clear correlation between the upper- and the lower aquifer. The river and the upper and lower aquifers is also showing a clear correlation. A numerical groundwater model is constructed to examine the collected data and the uncertainties in the hydraulic parameters of the aquifer. Scenarios is formed to look at the risk of polluting the drinking water well in the aquifer..

1. Introduction

Groundwater is an important resource. It has an advantage as drinking water, compared with surface water. It is protected in the ground and filtration depending on the geology and topography makes the groundwater cleaner and more hygienic. As drinking water, groundwater gives smaller seasonal variations in terms of temperature and quality of the water. 15 % of Norway's drinking water is today groundwater. The use of groundwater in sparsely populated areas is increasing due to the water quality and hygiene. Groundwater supply is also often economical beneficial. Municipalities like Oppland and Hedemark has 50 % of the water supply coming from groundwater (NGU, grunnvann.no). To be able to utilize groundwater as a resource, knowledge is crucial. Lack of hydrogeological investigations can make groundwater management difficult, due to important information of the aquifer missing.

1.1. Aim of the study

Unconsolidated sediments in intermountain valleys provide strategic groundwater reservoirs for cities and villages in Norway. These aquifers consist of alternating geological layers that present large variations in hydraulic conductivity leading to multiple confined aquifer systems. Hjartdal municipality has an intermountain valley with unconsolidated sediments forming a two-layer system. The aquifers interaction with the surrounding hydrological parameter is important to understand in order to understanding the reaction pattern of the aquifer. A new road, E134, is built, crossing the aquifer at Gvammen, Hjartdal. The aquifer act as the drinking water reservoir for the community at Gvammen. An understanding of the aquifer is needed, to look at the impact the road would have on the aquifer.

The aim of this master is to look further into the hydrogeological conditions at Gvammsletta, Hjartdal. What is the characteristics of the layers in the multiple confined aquifer system? How is the to aquifers interacting? What is the role of the organic layer? Statistical analyses is used in order to get a better understanding of the correlation between the different hydrogeological parameters. A groundwater model was created in order to look at the parameters affecting the groundwater flow. Scenarios was made to look at the effect of the road on the aquifer.

1.2. Previous studies

Staten Vegvesen (Norwegian Road Authority) decided to make a tunnel along E 134 between Gvammen and Århus. Miljøgeologi AS was in 2002 writing a report on the hydrogeology of the area. They conducted water- and sediment analyses, installed piezometers and georadar measurements. Sweco started taking tests and monitoring the area in 2010. They have written several reports regarding the area. Sweco collects the data for this thesis.

2. Background

2.1. Location

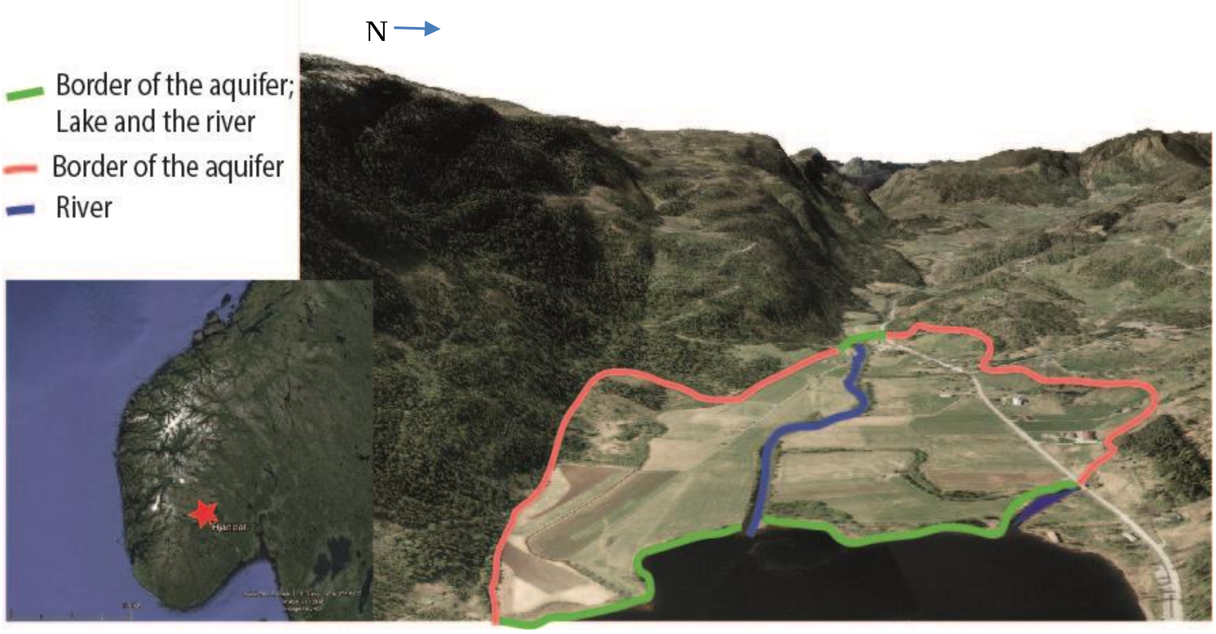


Figure 1: The study area. (maps.google)

The aquifer investigated is situated in Hjartdal municipality, Telemark county 150 km west of Oslo. The aquifer is situated in a valley plain called Gvammsletta (fig. 1), it is 1,22 km long, and variable width, from 0.8 km at the widest to 250 meters in the upper section. Gvamsletta contacts a 2.6 km long lake, Hjartsjå, in the east. Gvammsletta is a flat area, increasing 70 cm per 100 meters. The south side has steep mountain hills covered by forest. The terrain at the north side have a gentler slope. The north side have private houses, a grocery shop and a power plant. There is 30 houses using the water work at Gvammen. The main road between Oslo and Haugesund, E 134, is passing on the north side. A river is dividing the area in the middle of the valley plain. There is a power plant at the northeast side of the study area, releasing water into Hjartsjå from a dammed lake. The water is released through a short river flowing from the road (fig1). The valley plain is agricultural land consisting of crops (fig 2).

Figure 2: The farmed land covering large part of the aquifer.

2.2. Geology

The study area is situated in a valley surrounded by mountains of quartzite. During the last glacial period, Weichsel, sediments were deposited on the valley floor forming a delta plain. The sediments were most likely deposited by fluvial- and glasifluvial processes~~.~~

The primary deposition at Gvammsletta is a small melt water delta, deposited above marine limits (fig. 2). Later the delta eroded due to the lowering of the base level of erosion. The re-sedimentation of the melt water delta led to a lower laying delta, today positioned in Hjartsjå Lake. Periods with increasing temperatures led to flooding of the delta, depositing organic matter on the top layer and cross bedding (fig. 3). Parts of the area had peat formation. Flooding led to a cover of sediments over the organic layer (fig. 3). The natural meandering river is today a straight path because of human modification by making crops and agricultural land in the area (Miljøgeologi, 2001).

This means that the deposition in the valley plain mainly consists of three layers or zones. A lower layer consisting of the primary meltwater delta, an interlayer consisting of organic matter and peat, and an upper layer consisting of flooded sediments and moraine material from the glacier.

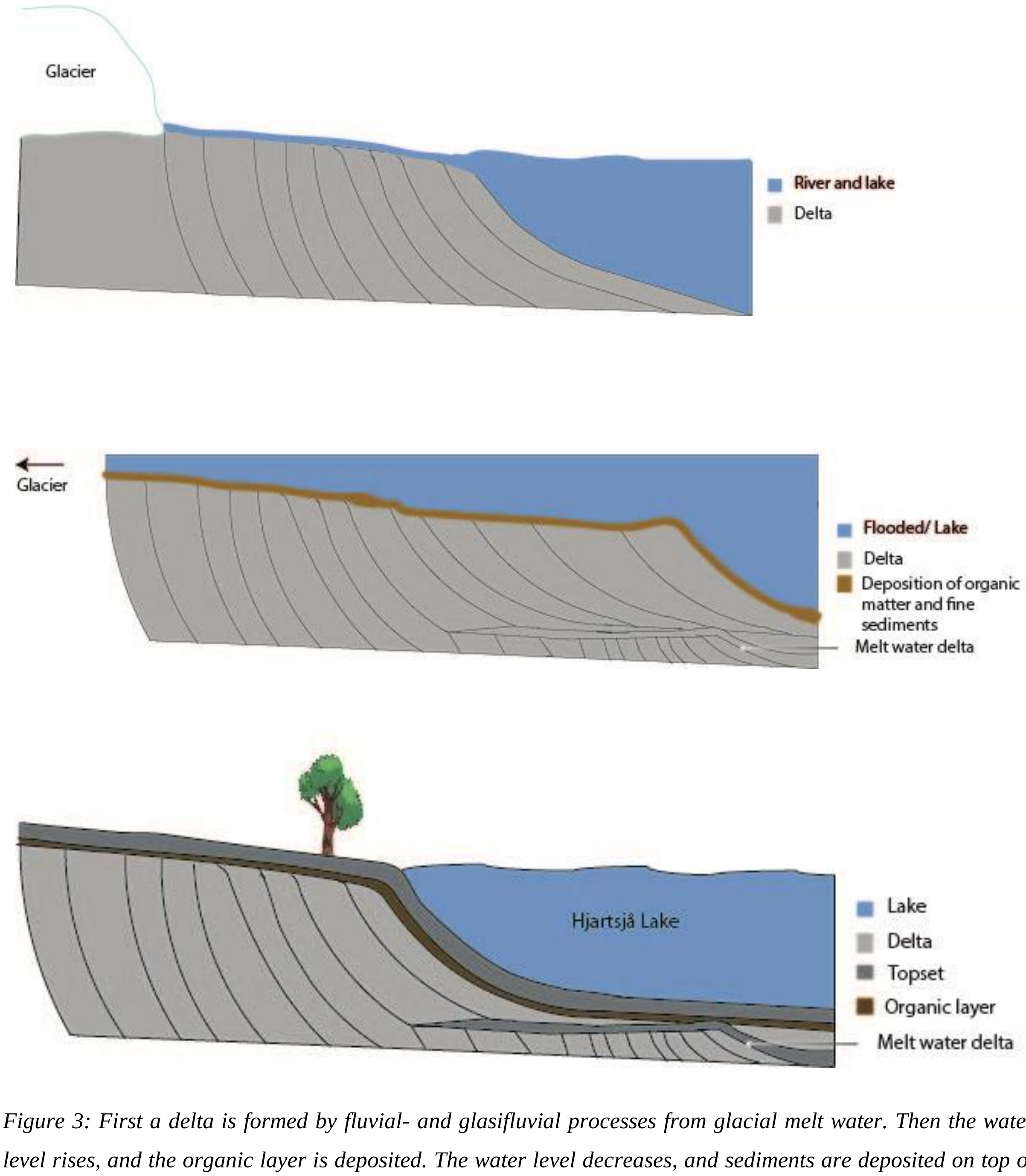


Figure 3: First a delta is formed by fluvial- and glasifluvial processes from glacial melt water. Then the water level rises, and the organic layer is deposited. The water level decreases, and sediments are deposited on top of the organic layer, which is the condition~~s~~ found at Gvammsletta today.

Today the valley plain consists of patches of silt- to sandy material in the topset, the rest of the area mainly consisting of coarser flood sediments of sand and gravel with rocks and blocks (figure 4 and figure 5). This is most likely the cross bedding of the delta. Analyses of flushed sediments, done by Miljøgeologi AS, are indicating medium to well sorted sediments in the delta (Sweco, 2013).

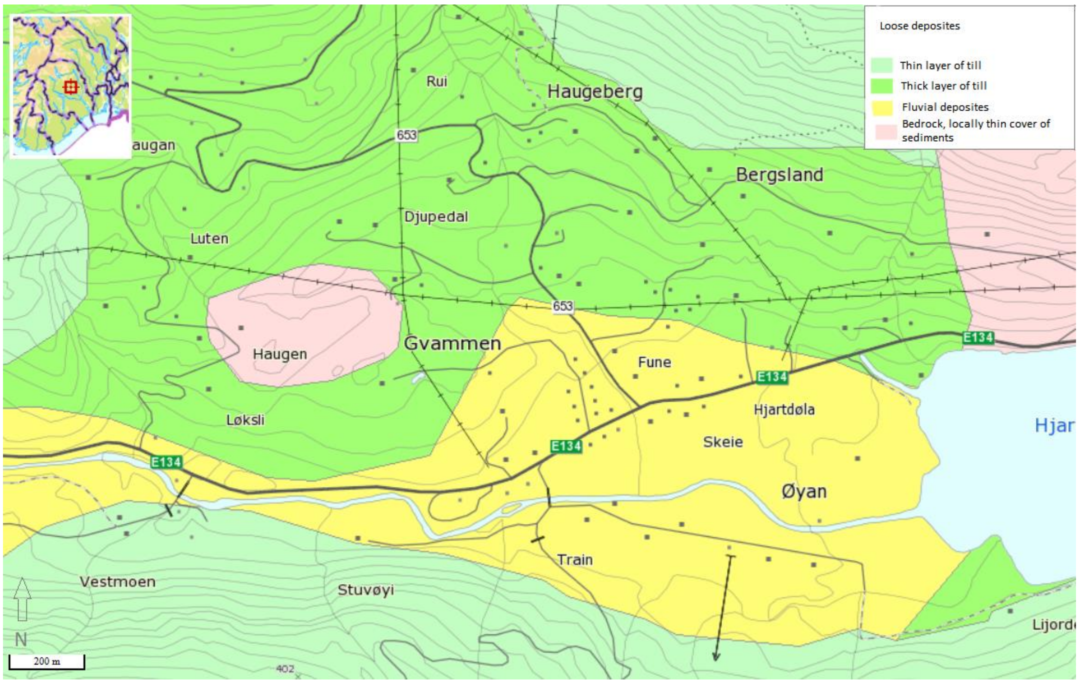


Figure 4: A map over the loose deposits at Gvammen (Modified from The Geological Survey of Norway).

Figure 5: A picture of moraine material on the south side of the valley.

The bedrock forms the base of the valley and the mountainsides. The regional geology of the county of Telemark consists of a thick Meseoproterozoic metasedimentary sequence (1500Ma-1100 Ma). The study area is a part of the Seljord group. Seljord group consists of quartzite, quartzite conglomerate, quartz shale, calcareous rich quartz shale and dolomite intrusions (Laajoki et.al, 2000). Field observations, from the tunnel entrance at the south side, exposes highly fractured quartzite with deposited mica. The north sides does not show visible bedrock outcrop. The study area have not been geological mapped by anyone. The mapped area surrounding the study area consists of Seljord group in the south, and the north side consists of gabbro and amphibolite or quartzite (ngu.no).

2.2.1. Sedimentary logs

In order to get a better understanding of the geological properties in the area 15 sediment cores were collected by Miljøgeologi AS. All the cores were taken in the east part of the study area (fig 6). The sediment cores have different depths, with the deepest at 42 meters below ground (table 1).

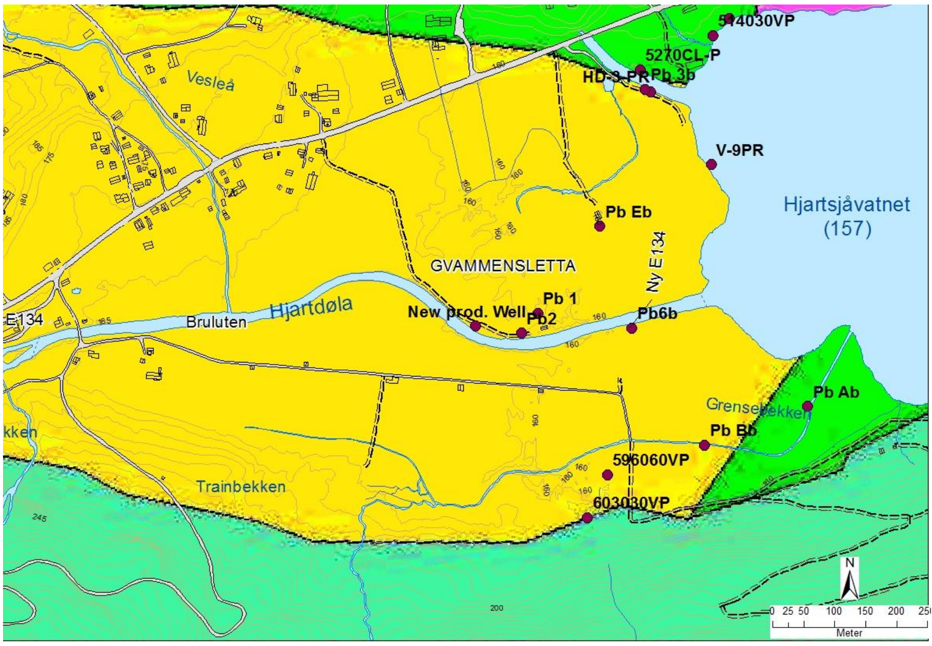


Figure 6: An overview of all the wells in the Gvammen area, the areas with purple circles indicate where there is sediment logs. The yellow area is representing the fluvial deposits, and the green area is till.

- Well Pb 3 is 16,5 meters. From the top to the bottom; 3 meters of sand and gravel before a 1 meter thick organic layer of peat is reached. Then there is alternating layers of sand and gravel intersected by two new organic layers at 8 and 11 meters, both 1 meters thick.
- Well PbE is 17 meters deep. It consist of; 3 meters of coarse sand on the top and 6 meters of fine sand with organic matter. The last 8 meters is coarsening upwards from medium sand to fine gravel. Well Pb 1, Pb2 and the new production well for the waterworks is all in the same area. Well Pb1 is 17 meters deep. It consists of (from top to bottom); 4 meters of sand with gravel and coarser sand with rocks, 3 meters of medium- to coarse sand with organic matter, then straight underneath the organic layer comes a thin layer of medium sand, whereas the last 10 meters consist of sand with gravel.
- Well Pb2 is also 17 meters deep. From top to bottom: gravel with rocks coarsening upwards to sand with gravel form 4 meters. Then 3 meters of medium sand with organic content, the remaining 10 meters is sand with gravel.
- The new production well is 41 meters deep. From top to bottom: 2,5 meters of coarse gravel, 0,5 meter of organic material, 3 meters of silt and organic material and 15 meters of coarse gravel, alternating with coarse sand. Getting finer towards the bottom.

- Well Pb6 is 18 meters deep. From top tobottom: 4 meters is fining upwards from gravel to silt, then 3 meters of sand and gravel. Underneath that is 10 meters of sand and gravel with fragments from wood, and a 1 meters layer with sand and gravel at the bottom.
- Well PbA is 17 meters deep. From top to bottom: 3 meters of coarse sand, 6 meters of find sand with organic material and the last 8 meters is coarsening upwards from clay with silt at the bottom to find sand.

7 shorter sediment logs were also collected (descriptions are done from the bottom towards the top for each core).

- 5270CL-P is 10,5 meters deep. The 3,5 meters at the bottom of the sediment core is fining upwards from gravel and sand to fine sand. Then a 4 meters thick organic rich layer on top, consisting of gravel to find sand in layers with clay and organic material. The organic content is high. The last three meters at the top is fining upwards from sand mixed with gravel, to sand and silt.
- 5100-15VP is also 11 meters deep. The lowest 8 meters consists of silt and sand, with a 1 meter peat layer on top mixed with sand. The 2 meters at the top is fining upwards from sand mixed with silt to sand, silt and clay. 5140-30VP is 10 meters deep. The 8 meters at the bottom sand with some silt in the top to meters. An organic layer at 1 meter above the sand is consisting of sand and silt with wooden particles. The top 1 meter is sand and silt.
- 5960-60VP is 10,5 meters. The lowest 8 meters is layer with silty sand at the bottom, then a layer of sand, with silt on the top. Then a 1,5 meter thick layer of humus and silt. Half a meter of sand with silt on the top.
- 6030-30VP is 5 meters deep. The 4 deepest meters are swamp at the bottom with peat with gravel at over, and a layer of peat on the top. The top 1 meter is sand and silt.
- HD-3-PR is 17 meters. The lowest meter is a mixture of sand, silt and clay. The log consist of several open spaces of question marks, where the content is unknown.
- V-9PR is 8 meters deep, consisting of layers of sand with gravel and sand with gravel and humus in total 1 meter. On top of this is a 4 meters thick organic layer with humus mixed with sand and gravel. On top a meter thick layer of sand and gravel.

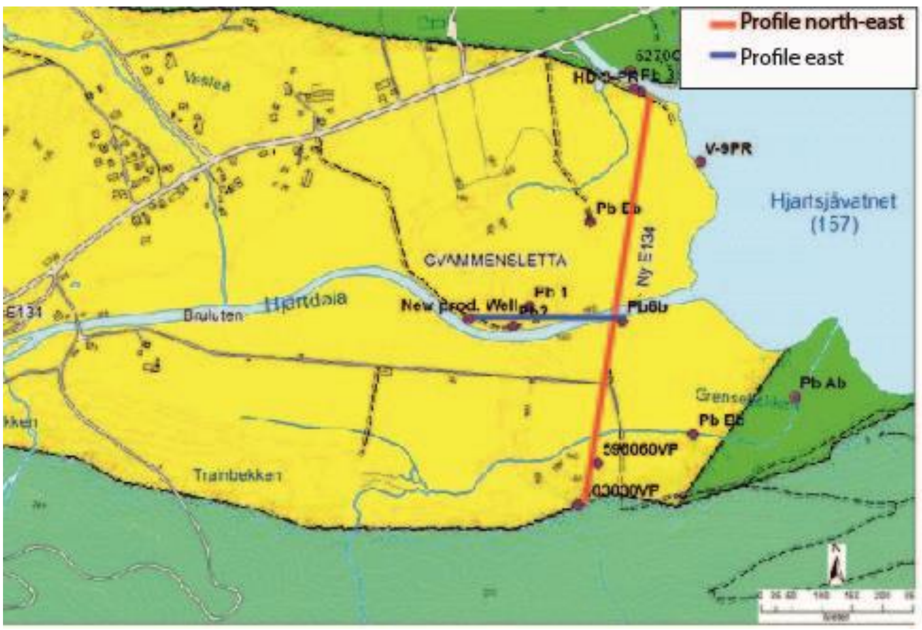
Table 1: Representing the sediment cores. The colored squares is representing the organically rich sediments.

m.a.s.l.	Pb 1	Pb 2	Pb Ab	Pb Bb	Pb Eb	PB 3b	PB 6b	Ny	5270CL-P	5100-15VP	5140-30VP	5960-60VP	6030-30VP	HD-3-PR	V-9PR
	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description	Description
160,5-160,0		Gravel with cobbles						Pebbels							
160,0-159,5	Mix of cobbel, gravel and sand						Silt and fine sand						Sand and silt material		
159,5-159,0					Coarse sand										
159,0-158,5							Sand		Sand and silt			Sandy silt	Peat		
158,5-158,0				Fine gravel		Sand and gravel				Sand-clay-silt		Silt + humus		Sand	
158,0-157,5	Sand with gravel		Coarse sand				Gravel	Org. Matr.	Sand and gravel				Peat with gravel		
157,5-157,0		Gravel with cobbles						Silt and organic matter		Silt with sand	sand and silt			Sand- gravel material	
157,0-156,5									Gravel and sand			Silt	Peat with gravel		
156,5-156,0		Medium sand with organic matter			Fine sand with organic matter					Peat with sand	Sand, silt with wooden fragments			?	Sa-Gr
156,0-155,5	Medium sand						Sand and gravel					Sand	Peat	Sa-Gr mat.	
155,5-155,0				Fine sand with orgnaic matter		Sand, gravel and peat		Silt and organic	Gr-fine sand with layers of clay and organic matter	silty sand	Silt and sand			Gravel - sand	Sand with gravel and humus
155,0-154,5	Medium to coarse sand with organic matter		Fine sand with organic matter									Sand		?	
154,5-154,0						Sand and gravel		Pebbels		Silty sand	Sand and silt				Sand with gravel
154,0-153,5												Sand			
153,5-153,0		Sand with gravel				Sand and gravel with cobbles		Gravel		Sandy silt	Sand				Sand with gravel and humus
153,0-152,5	Medium sand						Sand and gravel with wood fragments					Silty sand			
152,5-152,0								Gravel and sand	Lots of org.	Silty sand	?			Sa-Gr-Si materiale	Sand with gravel and humus
152,0-151,5	Sand with gravel								Fine sand			Sandy sillt			
151,5-151,0						Sand and gravel		Coarse sand		Silty sand	Sand			?	Sand
151,0-150,5									silt and fine sand			Silty sand			
150,5-150,0					Fine gravel	Organic		?		Sandy silt	Sand			Sa-Gr material	Sand with gravel
150,0-149,5				?		Sand and gravel			?			Silty sand			
149,5-149,0			Fine sand					Gravel and coarse sand		silty sand	Sand			Gr-Sa material	Sand
149,0-148,5									Gravel and sand			?			
148,5-148,0								?		silty sand	?			Gr-sand	
148,0-147,5														?	
147,5-147,0						Peat		Gravel and coarse sand							
147,0-146,5															
146,5-146,0				Fine sand		Sand and gravel		?						Gr-sand	
146,0-145,5			Silt with sand												
145,5-145,0								Pebbels						Sa-Gr material	
145,0-144,5															
144,5-144,0					Medium sand			Fine gravel						?	
144,0-143,5															
143,5-143,0				Fine sand				Coarse sand							
143,0-142,5			Silt with clay				Sand and gravel								
142,5-142,0								Sand						Sa-Si-Le materiale	
142,0-141,5															
141,5-141,0								Gr-Sa							
141,0-139,5															

2.2.2. Aquifer geometry

The aquifer is naturally limited by the mountains on both the north- and south side of the valley, and the bedrock underneath the delta plain. This makes the aquifer approximately 0.8 km at the widest, getting narrower while moving westward. The depth of the bedrock is at least 41 meters, which is the deepest drilled without reaching bedrock. Studying all the sediment cores there is a clear division between three different layers in all the cores. First there is a 3-8 meters thick layer of sediments at the top. In the middle there is an organic layer varying in thickness, from 1 to 10 meters with an organic content up to 50 %. This layer is thinning in the westward direction and is very compact, opposed to the sediments both on top and below. Underneath the organic layer, on the bottom is a layer consisting of sand and gravel. Based on these tree layers with different composition, there is most likely a groundwater systems consisting of two aquifers separated by the middle organic layer.

The layers are varying in thickness along the two profiles that were interpolated (fig. 7). The interpolated profiles is showing how the organics layer is changing in northeast direction (in the middle) and in east direction (at the bottom). The organic layer is divided into three different layers in well 3a. The profile at the bottom is clearly showing how the organic layer gets thinner in the westward direction.



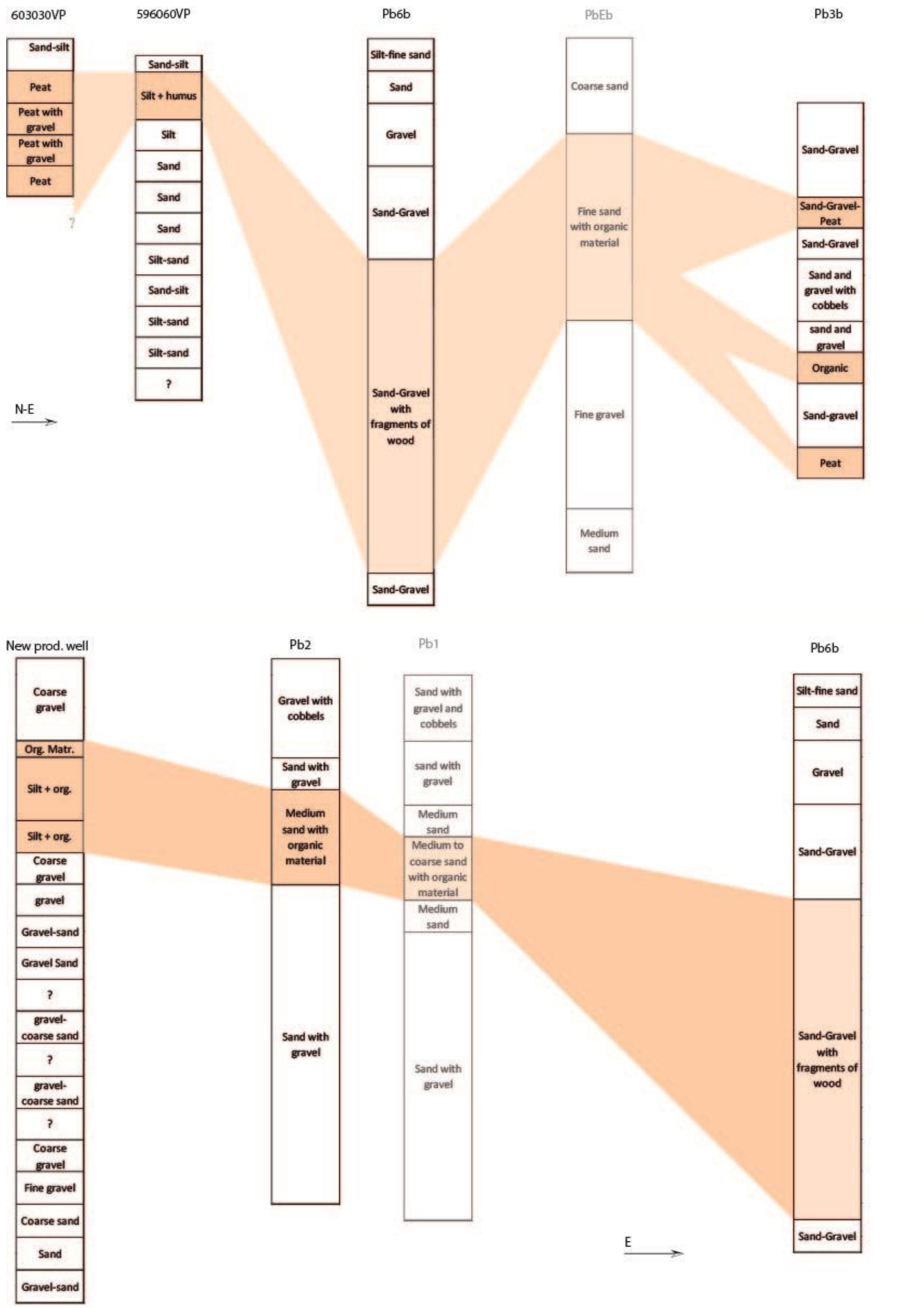


Figure 7: The map is showing the placement of the two interpolated profiles. The profile in the middle represent a profile of the layers in the aquifer in northeast direction. Sediment core 603030-VP is marked with a question mark at the end, because the depth of the organic layer is unknown. The profile at the bottom shows how the

organic layer is thinning in the westward direction. The light brown color representing the organic layer. Well Eb and well 1 having lighter color because it is close to the profile line.

A conceptual model is represented, with a profile from west to east in the aquifer (fig 8). It is estimated that the organic layer gets thinner and thinner before it disappears.

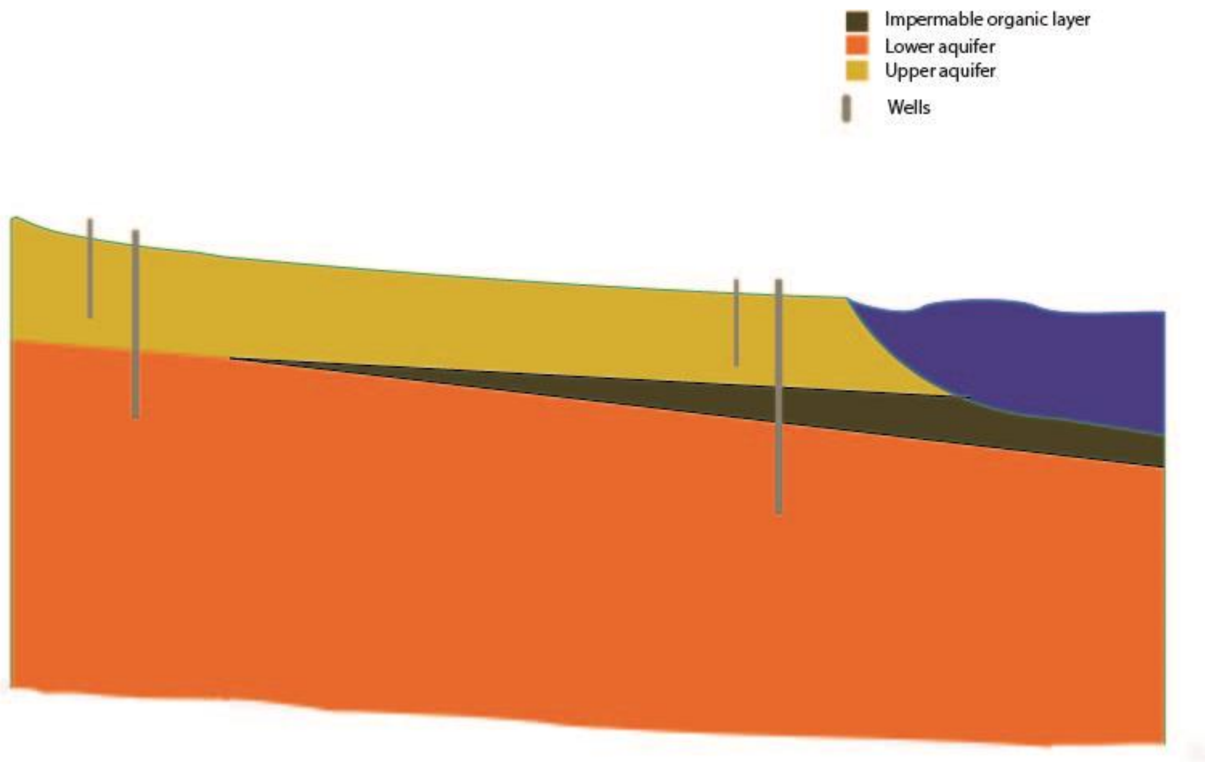


Figure 8: A conceptual model showing how the organic layer is thinning and disappearing westward. As a result of the organic layer there are two separated aquifers. A profile of the aquifer, not true to scale.

2.3. Data

In this section all the data available for this study are presented.

2.3.1. Time series

Time series is a continuous measurement of a variable, which is describing a continuing process (Løvås, 2004). The time interval chosen for doing the registration is crucial for capturing variations in the variables over time. For example measurements of precipitation once a month will be too seldom to see the effect of the rain on a lake (Iden, 1991). In this study the interval of registration is one day.

Time series analyses has four statistical techniques trying to explain the variations in the data:

- Trend: indicating a long-term trend, for example a climatic change.
- Seasonal variations: Indicating a pattern over days, months or years.
- Auto correlation: A dependency between the different variables, besides the seasonal variations and the trend.
- Random variation: The changes that cannot be explained by any of the above factors (Løvås, 2004).

2.3.2. Wells and measurements of the hydraulic head

The aquifer at Gvammsletta has 2 production wells belonging to the water work in the area, and 25 observation wells (fig 6), where 14 of the observation wells are in the lower part of the aquifer, and 11 wells in the upper part of the aquifer. The wells are named starting with Pb then a number, and a letter a or b at the end. A is representing the shorter well in the upper aquifer, and b is representing a deeper well in the lower aquifer. Different wells have been monitored for various periods, and all the wells have been manually measured with varying time interval (every second months to every six months) since 2010. The wells were drilled in different periods by several companies. The old production well was the first well drilled, then Miljøgeologi AS started looking at the hydrogeology in the area and drilled the wells around the water work in 2004. Multiconsult AS also did some work in the area substituting with some of the wells and Sweco complimented with several wells in 2010. Table 2 shows an overview of all the wells in the study area.

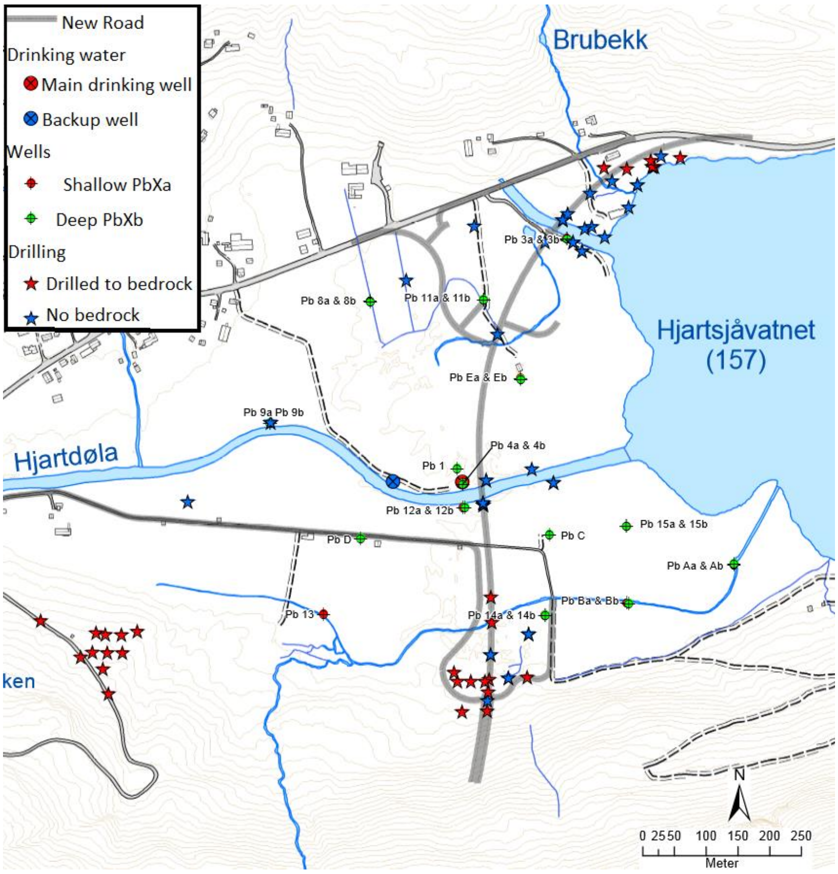


Figure 9: A map showing the different well locations.

Table 2: An overview of all the wells in the study area.

Well	Upper and lower aquifer
Pb 1	Lower
Pb 3a	Upper
Pb 3b	Lower
Pb 4a	Upper
Pb 4b	Lower
Pb 8a	Upper
Pb 8b	Lower
Pb 9a	Upper
Pb 9b	Lowe

Pb 11a	Upper
Pb 11 b	Lower
Pb 12a	Upper
Pb 12b	Lower
Pb 13	Upper
Pb 14a	Upper
Pb 14b	Lower
Pb 15a	Upper
Pb 15b	Lower
Pb Aa	Upper
Pb Ab	Lower
Pb Ba	Upper
Pb Bb	Lower
Pb C	Lower
Pb D	Deep
Pb Ea	Shallow
Pb Eb	Deep
Old production well	Deep
New production well	Deep

Table 3 is presenting the death of the filters at the wells, the length of the filter and the type of pipe used for the well.

Table 3: This table is presenting the elevation and the length of the filter in the aquifer, the type of filter and type of pipe used for the different wells.

Well	Filter top	Filter bottom	Filter	Type of pipe
Pb 1	145,43	144,43	1 m	5/4"
Pb3a	150,713	151,713	1 m	5/4"
Pb3b	?	?	1 m	5/4"
Pb4a	154,584	155,584	1 m	5/4"

Pb4b	139,473	140,473	1 m	5/4"
Pb8a	156,328	155,928	1 m	5/4"
Pb8b	141,826	141,426	0,4 m filter of bronze	Open standpipe
Pb9a	157,077	156,077		5/4"
Pb9b	147,143	146,743		5/4"
Pb11a	155,534	155,134	1 meter filter, 5 -10 cm sump	PEH
Pb11b	138,918	138,518	0,4 m filter of bronze	Open standpipe
Pb12a	156,984	155,964	1 meter filter, 5 -10 cm sump	PEH
Pb12b	144,82	143,82	0,4 m filter of bronze	Open standpipe
Pb13	158,578	157,578	1 m	5/4"
Pb14a	155,552	154,552	1 m	5/4"
Pb14b	140,037	139,637	1 meter filter, 5 -10 cm sump	PEH
Pb15a	156,149	155,149	0,4 m filter of bronze	Open standpipe
Pb15b	142,3358	141,9358	1 meter filter, 5 -10 cm sump	PEH
PbAa	154.027	153,027	0,4 m filter of bronze	Open standpipe
PbAb	142,982	141,982	1 meter filter, 1 meter sump	PEH
PbBa	144,349	143,349	1 meter filter, 1 meter sump	PEH
PbBb	144,349	143,349	1 meter filter, 1 meter sump	PEH
PbC	145,751	144,751	1 meter filter, 1 meter sump	PEH
PbD	147,492	146,492	1 m	5/4"
PbEa	154,527	153,527	1 m	5/4"
PbEb	154,482	153,482	3 meter filter, 1 meter sump	PEH

Automatic groundwater measurements is carried out in 18 wells in the study area. The data was collected in two periods. The first period from 10.02.2011 until 11.04.2012. In this period 5 different sites were monitored, with two wells at each site, one well in the upper aquifer and one well in the lower aquifer (in total 10 wells). The data collected are used for comparing the characteristics of the upper- and lower aquifer. Well 14a and 14b was measured in this period, which are placed near the tunnel opening (fig 10). The data from these two wells behave different then the data from the other wells in the aquifer (fig. 11). Then, in the lower aquifer the head suddenly falls 1.36 meters from 09.09.2011 to 10.09.2011. With the drop in the lower aquifer, the upper and lower aquifer gets the same pressure head for 5 months, before the lower aquifer start to increase in pressure-head again. This might indicate a broken pipe or an error in the diver, and this data is therefore not used in this studies.

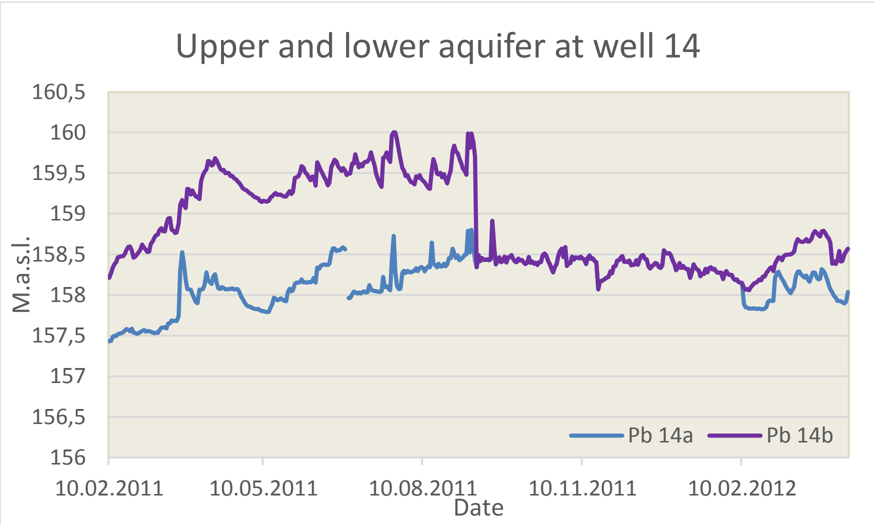


Figure 10: Representing the data from automatic measurements in upper and lower aquifer at well 14.

The second monitoring period is from December 2012 until September 2014. The period from July to September 2014 is missing barometric pressure measurements. Since these data are necessary to calculate the pressure in the divers to groundwater head, barometric measurements were taken from the same station as the temperature was measured. This is 27 km away in a parallel valley, this could lead to a bigger source of error than the measurements having the barometric pressure measured in the same area. In total 13 wells were monitored in this period, some of the wells only part of the period (table 4). All the measurements are from the lower aquifer.

There are several measurements done manually from 2010 until today, besides the automatic measurements. The manual measurements are normally conducted in all the wells. This are values that can be used to check if the diver data are correct.

Table 4: Showing the different wells and when they were monitored.

Wells	Upper or lower aquifer	February 2011-April 2012	Dec. 2012-Sept. 2014	August 2012-Sept. 2014
Pb1	Upper		X	
Pb 3b	Lower			X
Pb 4b	Lower			X
Pb 9a	Upper	X		
Pb 9b	Lower	X	X (until 23.08.2013)	
Pb 11a	Upper	X		
Pb 11b	Lower	X		X
Pb 12a	Upper	X		
Pb 12b	Lower	X	X	
Pb 14a	Upper	X*		
Pb 14b	Lower	X*	X (until 23.08.2013)	
Pb 15a	Upper	X		
Pb 15b	Lower	X		X
Pb Ab	Lower		X	
Pb Bb	Lower		X	
Pb C	Lower			X
Pb D	Lower		X	
Pb Eb	Lower		X	

* *Left out because of the inconsistent measurements.*

The heads in the upper and lower aquifer were measured from February 2011 until March 2012 (fig. 11). The data is showing a clear difference in pressure from upper aquifer to lower aquifer. There is almost 10 meters in pressure difference from upper aquifer until lower aquifer. The organic layer is most likely also representing an impermeable layer, making an artesian pressure in the lower aquifer. The blue line is representing the upper aquifer (fig. 11), showing that well 9a has the same pressure as the lower aquifer. This is the impermeable layer is not covering the whole area, and that the artesian pressure then disappears.

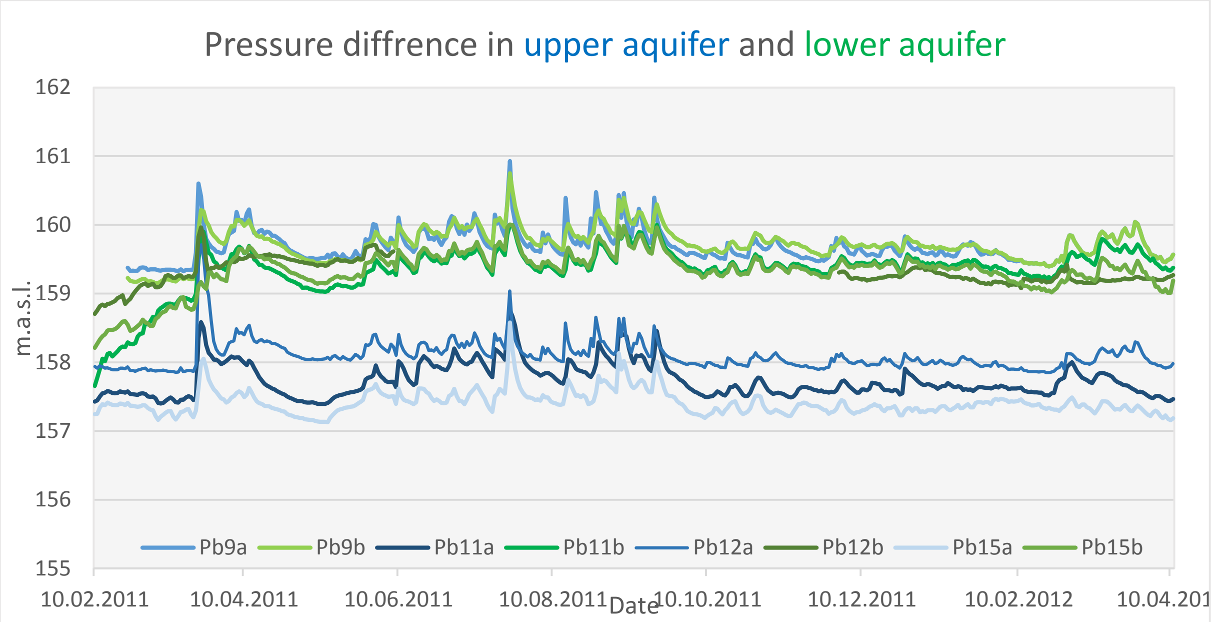


Figure 11: The pressure heads in the upper and lower aquifer.

2.3.3. Precipitation and temperature

The meteorological station at Gvamsletta is placed in the middle of the study area (fig. 12) and is only measuring precipitation. The temperature at Gvamsletta were measured by the use of a mini diver.

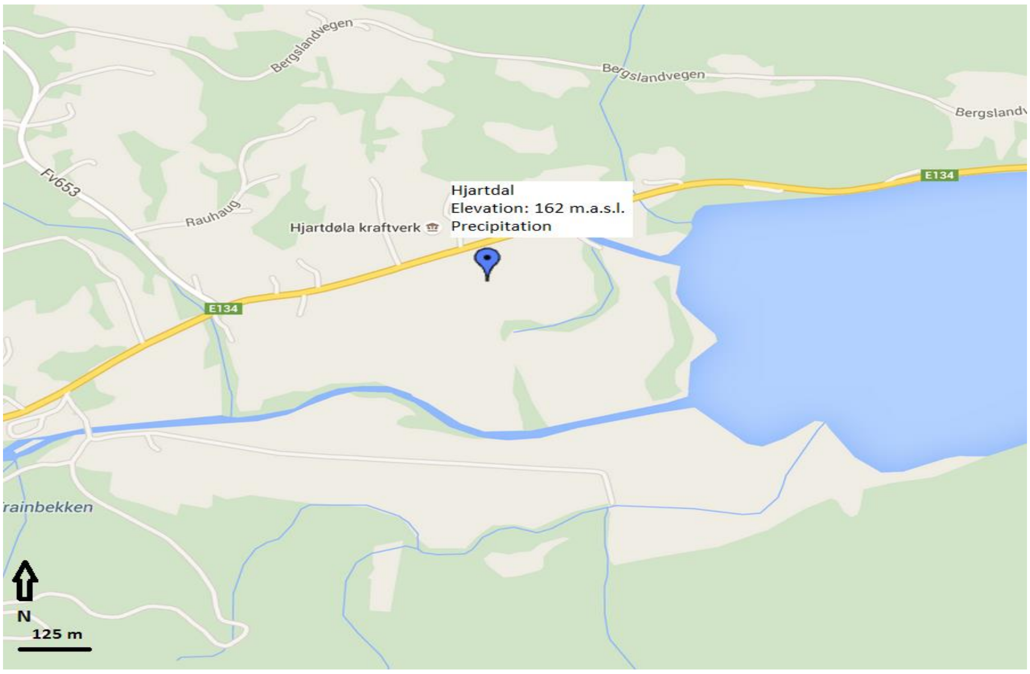


Figure 12: A map showing the location of the metrological stations.

At Gvamsletta is it normally temperatures below zero °C from November/December until March/April. Average precipitation is 76 mm/month evenly distributed over the whole year. Hjartdal is situated inland Norway, and has less precipitation than the coastal areas. Hjartdal has more precipitation during summer season and less in the winter season. The wind direction in Telemark is mainly north south, and since the valley strikes east west, it is little wind. The middle temperature is 16-17 degrees in June (fig 13). The annual average temperature is 3.9 °C the years the monitoring took place.

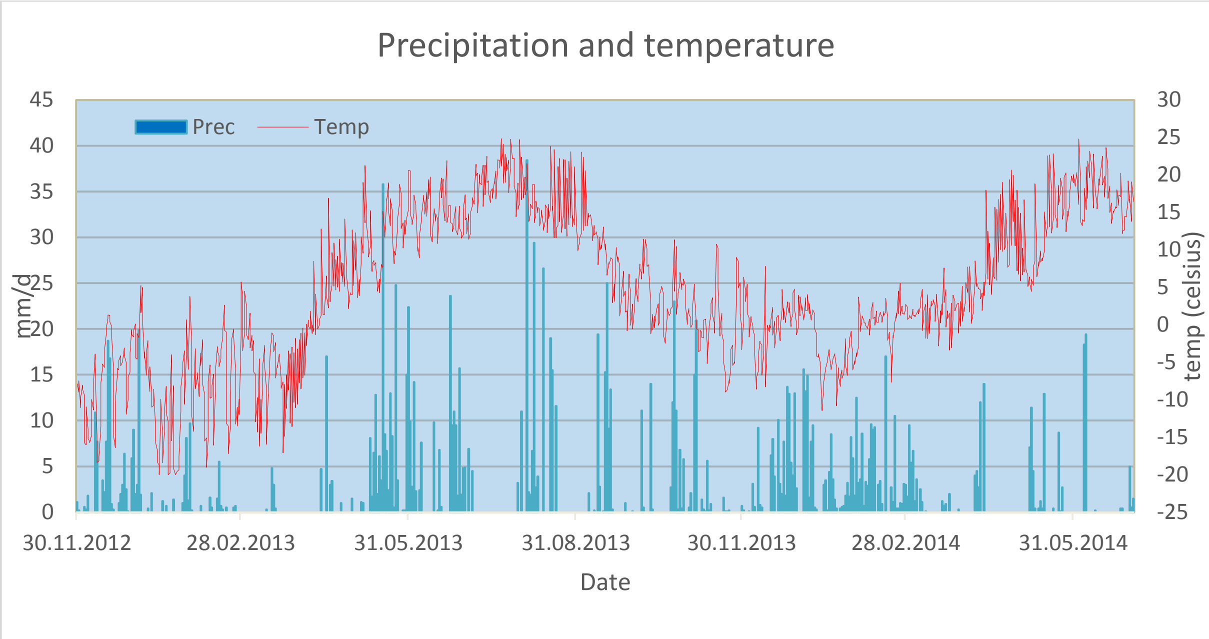


Figure 13: Temperature and precipitation at Gvamsletta. Temperature measured twice a day by a diver.

2.3.4. Lake and rivers

The study area have two creeks, two rivers and a drain from an old meander (fig. 14).

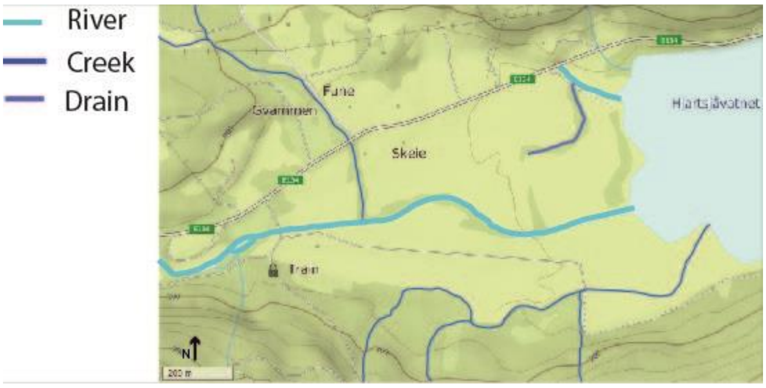


Figure 14: The surface water bodies in the study area.

The main river, Hjartdøla, is crossing the study area from west to east. The river start were the outlet of three lakes meet 11 km further north-west in the valley side. The study area is surrounding 1,25 km of the river, and the river is approximately 15 meters wide and an average of 2 meters deep channel. The river was naturally a meandering river, but was maneuvered into a straighter path by authorities. The catchment area of the river 364 km^2 (fig. 20) (Lancaster and Ludescher-Huber, 2009). The river was monitored by a diver from March 2011 until April 2012. The selected place for monitoring the river is represented with a blue circle in figure 15. The accurate altitude of the diver is not known, and it is therefore difficult calculating exactly the water level in the river.

Figure 15: The blue circles are representing the area where the diver was doing the measurements in the river and in the creek.

The data is representing much lower water levels in the river then expected (fig. 16), most likely because the diver is not placed in the middle of the river but on one side. This means these data are most likely not representing the real depth of the river, but they are representing the fluctuations in the river. The slope of the river is following more or less the slope of the delta plain. The flow is higher in the west end of the study area, and slowing towards the Hjartsjå Lake. The river has several types of fish, such as trout, eel and red-listed mussels (Elnan and Ledje, 2008). The river is used as spawning area for the trout.

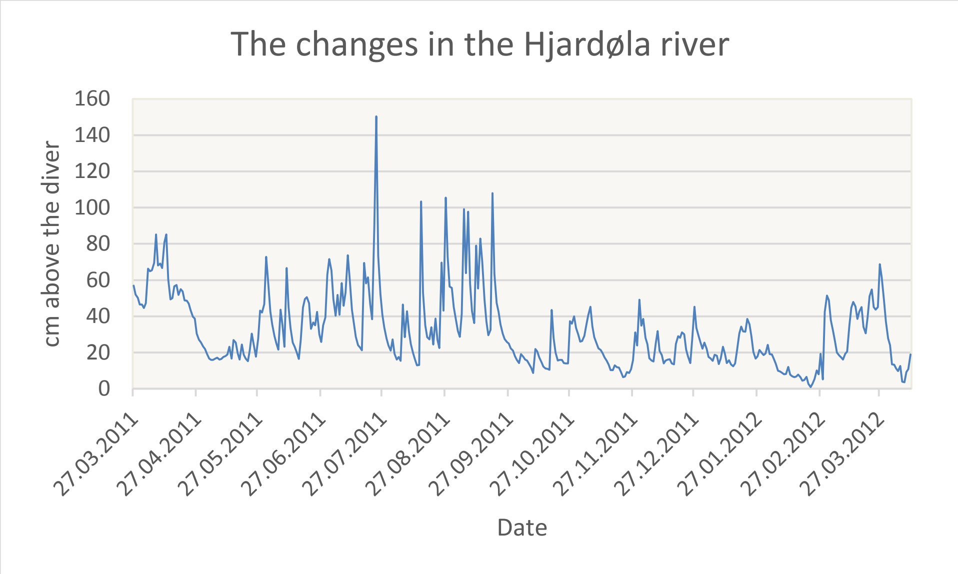


Figure 16: The graph is showing the changes in Hjardøla river.

Hjartsjå lake (fig. 17) is 2,6 km long and approximately 680 meters wide by the shore of Gvamsletta. The lake has several type of fish such as with fish and char. The lake and the river is used for fishing, the lake also has nice "beaches" for swimming. The catchment area of Hjartsjå Lake is 116 km^2, and is partly regulated due to several dammed lakes in the catchment area (Lancaster and Ludescher-Huber, 2009). The lake is 43, 5 meters at the deepest and has an average depth of 22 meters (NVE, 2015). In figure 10 is the lake level of Hjartsjå represented. The lake is monitored by a diver from June 2011 until May 2012. The average lake level is 156.8 meters above sea level. The lake level is having its peaks in during summer, August and September. The lowest levels is observed during April and November.

Figure 17: Picture of Hjartsjå Lake looking in southwest direction, towards the study area.

The catchment area of Hjartsjå Lake is 116 km^2, and is partly regulated due to several dammed lakes in the catchment area (fig. 18) (Lancaster and Ludescher-Huber, 2009). The lake is 43, 5 meters at the deepest and has an average depth of 22 meters (NVE, 2015). In figure 18 is the lake level of Hjartsjå represented. The lake is monitored by a diver from January 2011 until May 2012. The average lake level is 156.8 meters above sea level. The lake level is having its peaks in during summer, August and September. The lowest levels is observed during April and November.

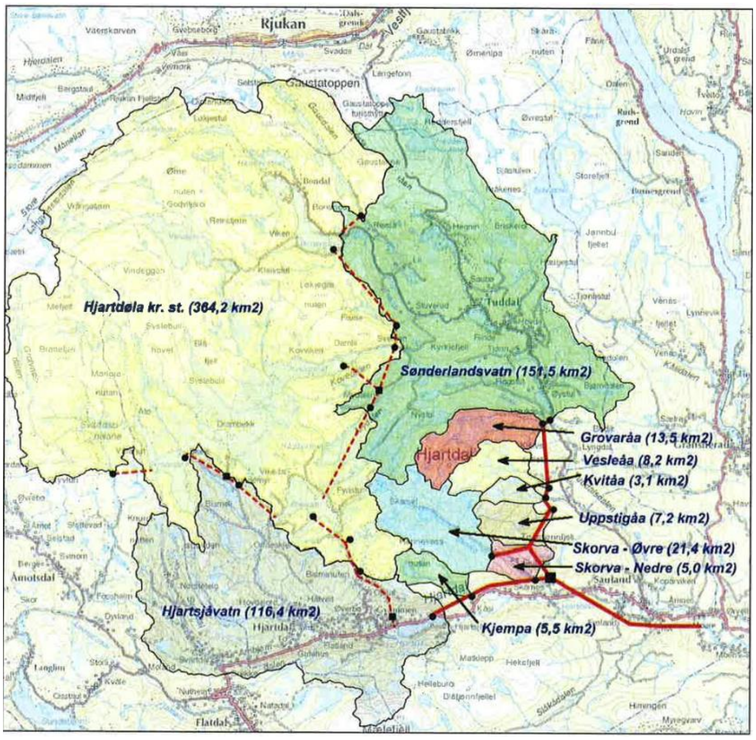


Figure 18: The catchment area of Hjartdøla River is marked in yellow, and the catchment area of Hjartsjå Lake is marked in the south part of the map (Lancaster and Ludescher-Huber, 2009).

The lake level of Hjartsjå is monitored by a diver from January 2011 until May 2012 (fig 18). The average lake level is 156.8 meters above sea level. The lake level is having its peaks in during summer, August and September. The lowest levels is observed during April and November.

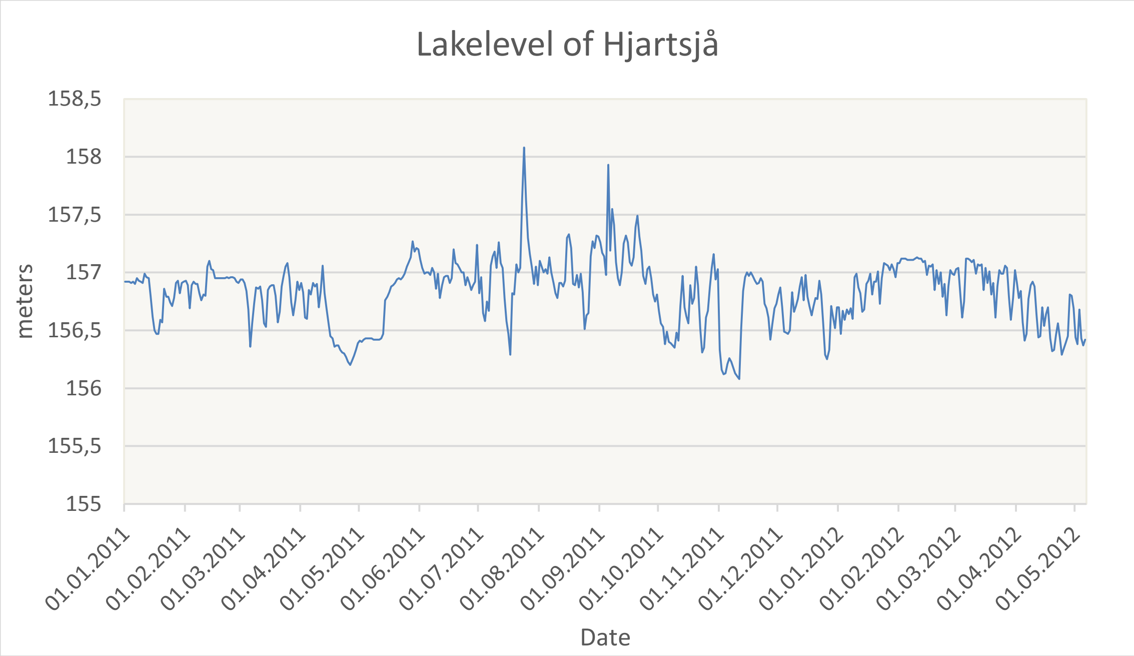


Figure 18: The graph is representing the lake level of Hjartsjå.

At the northeast side of valley plain, is an old meander left behind. It was earlier a part of Hjartdøla River. It is the last place at the valley plain where the wet mark environment is left behind. The meander is for most of the time covered by bushes and trees, with some parts open for the sun to get through. The meander is ligated from the water where Hjartdøla powerplant releases its water. There is still exchange of water through a culvert (Norwegian Public Roads, 2012). Today the meander function as a drain, changing between being dry and filled with water depending on the season and the amount of precipitation. The meander will be destroyed under the construction of the road, E134 passing this point.

At the south side of the study area there is a creek following the valley side, before it crosses the farmed fields and goes into Hjartsjø Lake (fig. 19). The measurements in the creek is missing data on the exact altitude of the diver, and it is therefore hard giving exact level of the water. The data shows that the creek dries out in end of March, April and May, this is the season when the snow starts to melt. The snow melting season in the mountains is in May and June, and then there is a sudden increase in the water level.

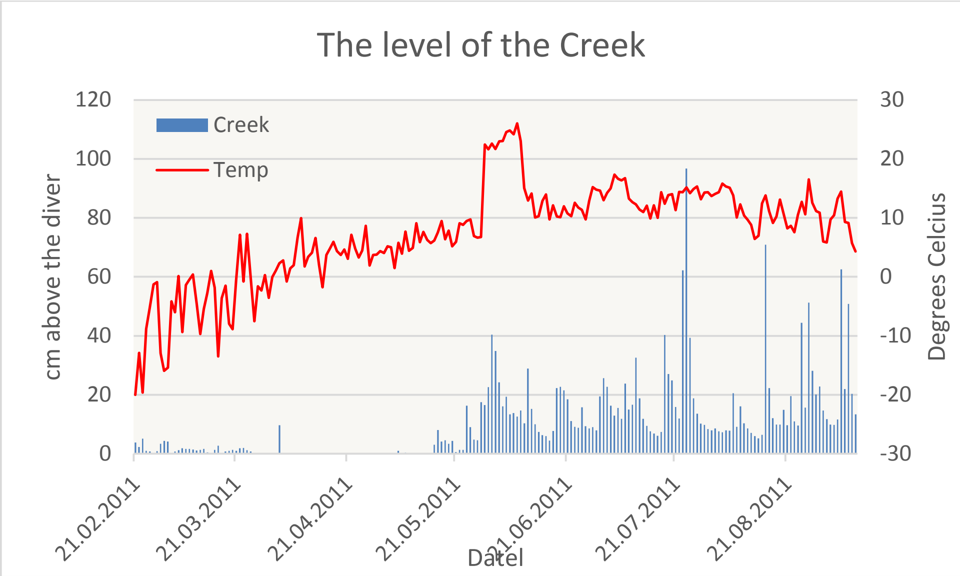


Figure 19: The level of the creek measured in cm above the diver. 0 cm means it goes dry.

There is a creek running down the mountainside at the north side of the valley, entering into Hjartdøla River. This creek has not been measured, but it has a constant flow. The level of the river is measured downstream this river.

There is also a river going from Hjartdøla Power Plant into the lake (fig. 20). The river is approximately 10 meters wide, and around 200 meters long. The rivers has not been monitored, but there is collected data from Hjartdøla power plant.

Figure 20: The river from the power plant running into Hjartsjå Lake.

The data from Hjartdøla Power Plant is given in m^3/s, and is calculated from the production of the power plant. This means that these data is only representing the water released from the power plant, periods without production releases no water and the flow will then be zero. The river flowing from the power plant do not go dry, so the flow from the power plant will not be the accurate flow of the river. These data can be used to look at the impact of the water released from the power plant on the hydrogeological system.

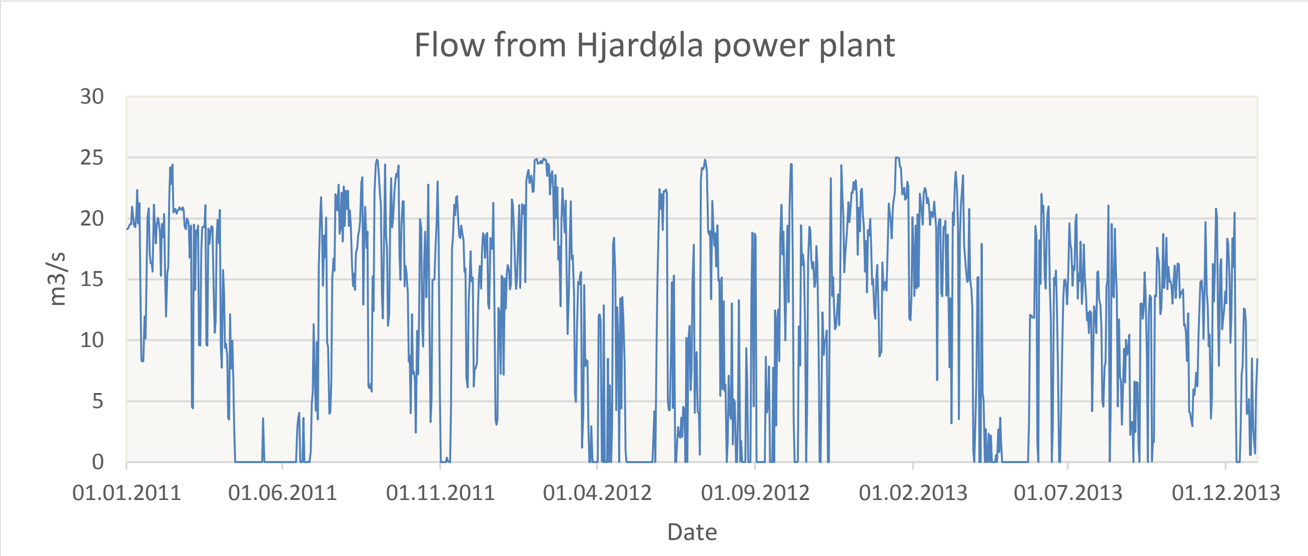


Figure 21: Flow calculated based on the production of the power plant.

2.3.5. Hydraulic conductivity

Miljøgeologi AS made grain size distribution curves for calculating the hydraulic conductivity in well Pb1 and Pb2. Sweco calculated the hydraulic conductivity for Pb2, PbAb, PbBb and PbEb (table 5).

Table 5: Representing the calculated hydraulic conductivities in the aquifer.

m.a.s.l.	Pb1	Pb2	PbAb	PbBb	PbEb
	K (Gust) m/s	K (Gust) m/s	K (Gust) m/s	K (Gust) m/s	K (Gust) m/s
160,5-160,0					
160,0-159,5					
159,5-159,0					
159,0-158,5	2.79E-04				
158,5-158,0					
158,0-157,5					
157,5-157,0					1.70E-06
157,0-156,5					
156,5-156,0	3.17E-04			9.10E-03	
156,0-155,5			1.60E-04		
155,5-155,0		4.06E-04			
155,0-154,5	5.76E-04				
154,5-154,0					1.60E-07
154,0-153,5		3.86E-04			
153,5-153,0	3.10E-04			1.20E-06	
153,0-152,5					
152,5-152,0		2.22E-04			
152,0-151,5	1.02E-04				
151,5-151,0					6.10E-07
151,0-150,5		5.76E-04			
150,5-150,0	3.69E-04			9.30E-08	
150,0-149,5					
149,5-149,0		2.78E-05			
149,0-148,5	5.76E-04				
148,5-148,0					2.10E-03
148,0-147,5		4.69E-04			
147,5-147,0	8.61E-04			2.80E-06	
147,0-146,5			4.20E-06		
146,5-146,0		1.03E-03			
146,0-145,5	2.61E-03				
145,5-145,0		2.35E-03			5.10E-03
145,0-144,5	1.29E-03				
144,5-144,0				2.10E-05	
144,0-143,5			1.80E-07		
143,5-143,0					
143,0-142,5					7.40E-04
142,5-142,0					
142,0-141,5				2.80E-05	
141,5-141,0			9.50E-08		
141,0-139,5					

3. Methods

The recharge and hydraulic conductivity was calculated from precipitation data and grain size analyses of the sediment logs. Sediment logs were also analyzed in order to get an understanding of the model geometry. Statistical analyses were conducted in order to look at the interactions between the hydrological parameters and the aquifer. Numerical modelling were then used to reproduce the functioning of the aquifer.

3.1. Statistical analyses

In order to get an overview of the hydrogeological system at Gvammsletta and look at the relationship between the different datasets, statistical analyses were conducted. This gives a good understanding of the data, and what it is representing. Correlation and cross-correlation were carried out in order to look at the relationship between the aquifer and the different hydraulic factors. It was also used to look at the relationship between the upper and lower aquifer, between the lake and the aquifers, and the effect of recharge on the aquifer.

3.1.1. Correlation

Correlation looks at the mutual relationship between two variables, without consideration of the seasonal characteristics. By using correlation it is possible to describe if there is a linear relation between two factors. The linear relation gives the correlation coefficient, which is an indication of the relationship between the two factors, e.g. the river level and the aquifer head. The correlation is defined as the covariance divided by the variables standard deviation:

$$\rho(X,Y) = Corr\ (X,Y) = \frac{Cov(X,Y)}{\sigma_X * \sigma_Y} \quad (1)$$

To estimate the empiric covariance with *n* observations:

$$S_{XY} = \frac{1}{n-1}\sum_{i=n}^{n}(X_i - \bar{X})(Y_i - \bar{Y}) \quad (2)$$

Two get a numerical value for the correlation coefficient *r*, the empiric correlation R is needed. Definition of R, taken into consideration eq. 2, will then be:

$$R = \frac{S_{XY}}{S_x * S_Y} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 * \sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (3)$$

Equation 3 has *n* observation couples (X_n, Y_n) with the empirical correlation R. R is a stochastic variable with a defined probability distribution, where the numerical value is the correlation coefficient *r*. The quality of R is increasing by the increase of observations, in this case it is the frequency of the measurement of the data (per hour, day or month) and the timespan of the data deciding the quality of R. Looking at correlation coefficient value *r*, instead of the unknown correlation ρ (eq. 1). *r* has the following interpretations:

- *r* is between -1 and 1.
- *The Absolut value* to *r* suggest the linear relation between the variables X and Y. Value 1 is indicating a perfect positive correlation i.e. both the heads in the aquifer, and the level of the lake increase simultaneously. Whereas a value of -1 is a perfect negative correlation. This means that the heads in the aquifer increases simultaneously as the level of the lake decrease. A value of 0 indicates no correlation and relation at all.
- *The sign* in front of the number indicates the direction of the correlation. Positive values indicate an increasing straight line, and negative values indicate a decreasing straight line. (Løvås, 2015)

The correlation coefficient is revealing to which extent a value can be guessed based on the values of the other variables (Statistical consulting group, 2015). The correlation coefficients can be calculated to identify the factors that influence the different classes of groundwater hydrographs (Moon, e.al, 2004). The strength of the correltion is taken from Dancey and Reidy`s (2004) (table 6). In these thesis is the all the values above 0.3 taken into consideration.

Table 6: The meaning of the values for the correlation coefficient.

Value of the Correlation Coefficient	**Strength of Correlation**
1	Perfect
0.7 - 0.9	Strong
0.4 - 0.6	Moderate
0.1 - 0.3	Weak

Value of the Correlation Coefficient	Strength of Correlation
0	Zero

3.1.2. Correlograms

Correlograms are used to present the results of computing values from one time series with values from a second time series. In this case correlograms is used to look at the hydrological parameters, the cross-correlation between them, and the delay (lag) of changes within the aquifer level, e.g. the effect of the precipitation on the lower aquifer. The first thing to consider with cross-correlation is the significance of the correlation, thus the predictability between the two time series (Wright State University, 2013).

The difference between cross-correlation and correlation are the seasonal variations taken into consideration. The correlogram is serial correlations (r_k) plotted against lag (k) (McCuen, 1941). The distance to the best fit determines the value of the lag. Looking at the cross-correltion between the aquifer head and the lake level as an example. The input is the independent variable and the output is the dependent variable (Lee and Lee, 2000). In this case it is assumed level of the lake is affecting the groundwater within the aquifer. The aquifers are treated as the independent variable, whereas the lake is the dependent variable. A peak (or a point) is identified in the aquifer to find the cross-correlation factor, and the same peak is identified in the interpolated values from the lake. The reason for the interpolation is because data in general is not evenly spaced. Depending on how well all the points fits, the cross-correlation value is calculated. The amount of days it takes from a peak in the dataset in the aquifer until the same peak is found in the data from the lake is the lag (figure 22). The result from the cross-correlation can have any value between -1 and 1, the same as the correlation (Wright State University, 2013).

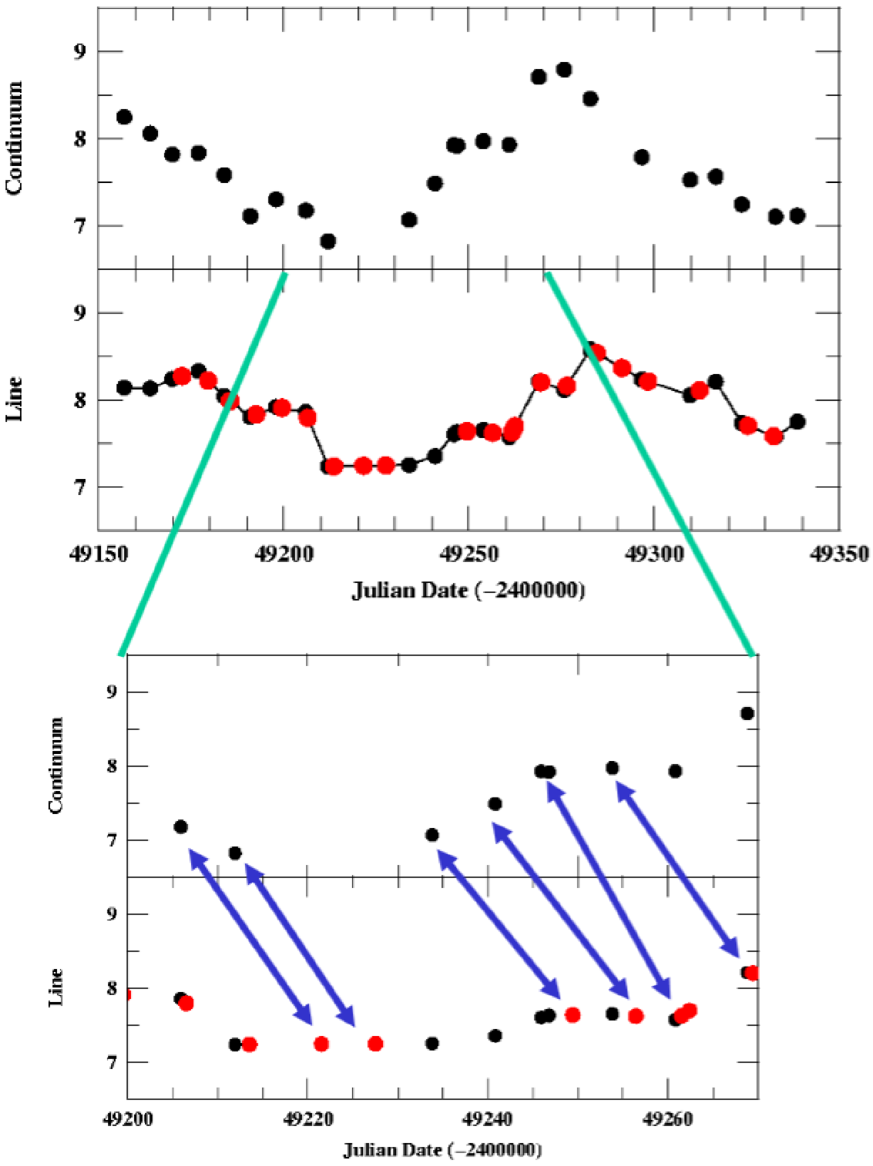


Figure 22: An illustration showing how cross-correlation works. Each dataset is matched with interpolated values from time series 2, the linear correlation-coefficient is then computed for all possible values of lag τ (B.M. Peterson).

3.1.3. Stata

All the statistical analyses produced in this thesis is completed by the use of the program Stata/SE 13.1. Stata is a general-purpose statistical program designed for researchers of all disciplines. The capability includes data management, statistical analysis and graphics, which is the properties utilized in this study. In this section the formulas used in Stata are presented.

The correlation command in Stat displays the correlation matrix or covariance matrix for a group of variables. The correlation matrix is constructed by calculating correlation coefficients by using casewise deletion; requesting correlation of variables x_1, $x_2, \ldots, x_k$, and the observations with missing data will not be used (Stata manual, 2013). The estimate of the product-moment correlation coefficient, ρ, is calculated by the use of equation 3. The mean of x, and $\overline{Y}$ (from eq. 3) is similarly defined (Stata manual, 2013);

$$\bar{X} = (\sum w_i X_i)/(\sum w_i) \qquad (4)$$

The cross-covariance in Stata is calculated by using the function of lag k for time series x_1 and x_2;

$$Cov\{x_1(t), x_2(t+k)\} = R_{12}(k) \qquad (5)$$

This function is not symmetric around lag zero;

$$R_{12}(k) \neq R_{12}(-k) \qquad (6)$$

The cross-correlation function is defined as;

$$\rho_{ij}(k) = Corr\{x_i(t), x_j(t+k)\} = \frac{R_{ij(k)}}{\sqrt{R_{ij}(0)R_{ij}(0)}} \qquad (7)$$

Where ρ_{11} and ρ_{22} are the auto correlation functions for x_1 and x_2 respectively. The sequence ρ_{12} *(k)* is the cross-correlation function and is drawn for lag $k \in (-Q, -Q+1, \ldots, -1, 0, 1, \ldots, Q-1, Q)$.

If ρ_{12} *(k)* 0 for all lags, x_1 *and* x_2 are not cross-correlated or has any form for relation. (Stata Manuel, 2013)

3.2. Modeling

A model is a tool to represent and understand large data sets, a mathematical way of representing a conceptual descriptions or approximations describing physical systems, in this case groundwater systems. A model will never become an exact description of the natural physical system or process. (Anderson and Woessner, 1992)

Mathematical models can be solved analytical or numerical. (Anderson and Woessner, 1992) In this case a numerical groundwater model is constructed which describe groundwater flow based on equations. As a consequence simplifications in geometry and aquifer properties and uncertainties in the values of the data required, a model will always be an approximation of the field conditions, not exact imitation. (Kresic, 2007)

According to Kresic does groundwater modeling have three different applications:

- To predict artificial or natural changes in the studied system.
- Use for descriptive purposes to analyses different assumption about its nature and dynamics. Can be used to plan future investigation.
- Study hypothetical systems to get a better understanding of principles of groundwater flow associated with general or specific problems, ex. models of contamination.

3.2.1. Numerical models

A numerical model work by dividing area of interest into cells, and the basic groundwater equation is solved for each cell considering the water balance. In this study the produced solution of the numerical model is defined in form of hydraulic heads at points, representing the individual cells.

3.2.2. GSM

In this thesis, Modflow was used with the interface developed by the US Department of Defense Groundwater Modeling System (GMS) to produce a groundwater model. GMS is a comprehensive graphical system for groundwater modeling, including tools for site characterization, model conceptualization, mesh and grid generation, and geostatistics as well as sophisticated tools for graphical representation of the model output. The program supports several types of numerical codes (Yousafzai et.al, 2008)

3.2.3. Mathematical background

The hydraulic conductivity depends on the properties of the geological ground. The pore volume and the interconnection between the pores are determining the hydraulic conductivity, where large pore volume and high interconnections give a high hydraulic conductivity. The hydraulic conductivity is defined as

$$K = -v * i \qquad (8)$$

v: Specific discharge (discharge/area)

i: hydraulic gradient (change in head divided by change in distance)

Transmissivity is a measure of how much water can be transmitted horizontally, it gives an indication of the water-bearing characteristics of hydrogeological bodies (Krásný, 1992). Transmissivity is defined as:

$$T = K * b \qquad (9)$$

b: saturated thickness of a unconfined aquifer (Freeze and Cherry, 1979).

Storativity of an aquifer is the volume of water the aquifer releases or takes into storage due to changes in the hydraulic head, and it is dimensionless. The physical mechanism releasing or storing water is not the same in unconfined and confined aquifers. Storativity for unconfined aquifers is:

$$S = S_y + S_s b \qquad (10)$$

Where S_y represent the specific yield, and S_s the specific storage. S_y is the ratio between the volume of water the unconfined aquifer will yield do to gravity drainage, and the total affected volume, the quantity of water which a unite volume of aquifer gives up by gravity. The volume remaining in the aquifer after the drainage is called specific retention. Specific yield is total porosity minus specific retention. Specific yield is given in percentage or decimal numbers. S_s is the amount of water a specific volume releases from the storage per unit change in hydraulic head while remaining saturated. Specific storage is given in m^{-1}. S_y is the dominant factor in an unconfined aquifer and porous sediments with small surfaces gives high specific yield. Storativity in a confined aquifer is $S_s b$ (Driscoll,1986; Kresic, 2007).

In order to describe groundwater flow two important physical principles need to be accounted for: Darcy's law and the law of mass balance.

Darcy´s law:

$$Q = -K\frac{\Delta h}{\Delta s}\,A \qquad (11)$$

A: area of the cross-section where the water flows true.

To know the groundwater flow in the whole aquifer the head *h(x, y, z)* is needed to be known throughout the aquifer. This distribution is not known, and the law of mass balance is needed. It states that no water can spontaneously disappear or appear at a particular point in the aquifer (Haitjema, 1995).

The continuity of flow is:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \qquad (12)$$

If one combine Darcy`s law (eq 11) and the continuity equation (eq 12) the result is a single basic second order differential equation governing steady state groundwater flow, called Laplace´s Equation:

$$\frac{\partial}{\partial x}\left[-k\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[-k\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[-k\frac{\partial h}{\partial z}\right] = 0 \qquad (13)$$

GMS uses a series of algebraic equations which is based on the conservation of mass and Darcy´s Law. GMS solves the governing equation for transient groundwater flow in 3D:

$$\frac{\partial}{\partial X}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) + Q_P + N + D = S_s\frac{\partial h}{\partial t} \qquad (14)$$

D: thickness of the aquifer

N: recharge

Q_p: pumping

h: unconfined aquifer

K: hydraulic conductivity

X,y,z: representing the different directions.

Modeling consists of three main steps:

1) Gathering necessary data from the field: Properties of the geological materials, groundwater levels and discharge into the area of interest. The amount and quality of the data is making the foundation for a good model.
2) Conceptual model: Reconstruct the area in a simple manner by including all the important characteristics.
3) Producing a numerical model in order to simulate the conceptual system.

The different models in a program is generally based on of these methods: the finite difference, the finite element or the analytical elements. GMS is mostly using finite difference method. One of the ways finite difference method is different from finite element method is that the grid is divided into orthogonal cells, GMS works by dividing the modeled area into rectangular cells where the head is solved for each cell. The head in one cell is related to the heads of the surrounding cells, where each cell has homogeneous properties. The size of the cells is determining the accuracy of the model. The geometry of the area and the stratigraphic layers will then be shaped by the use of grid (fig 23).

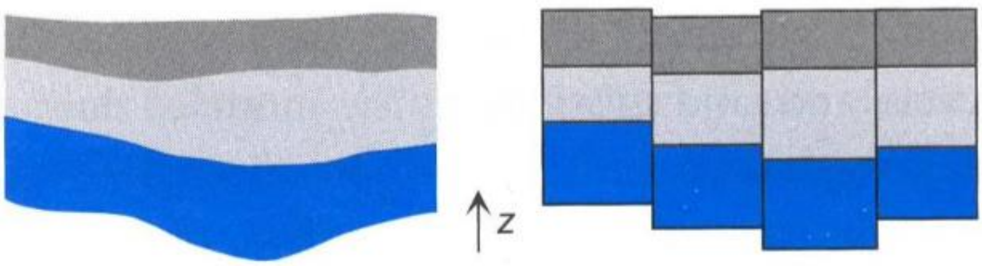


Figure 23: The left side is representing the naturel geometry of stratigraphic layers, the right side is the same stratigraphic layers reconstructed by cells.

3.2.4. Boundary conditions

The initial conditions consists of the known head distribution at an initial starting time of the model. There are three possible boundary conditions, which can be applied to any parts of a modelled domain (fig. 24):

- *The Dirichlet boundary conditions* is prescribing a constant head value. All the models should include a point with the first kind boundary in order to give a uniqueness to the solution of the model. If not the solution can only be determined up to a constant. This boundary condition will often represent large surface water body (lake, ocean).
- *The Neumann boundary condition* is a known flux boundary. The flux is the head gradient normal to the boundary. This boundary is also utilized when flux is zero, and the boundary of the model coincide with the streamlines.
- *Semipervious / mixed boundary conditions* specify the linear combination of head and flux. This boundary condition can be used to represent rivers separated from the aquifer by a riverbank. The discharge from the river to aquifer depending on the riverbed

leakage, and the difference in the riverhead and the surrounding cell heads. (Kinzelbach, 1986)

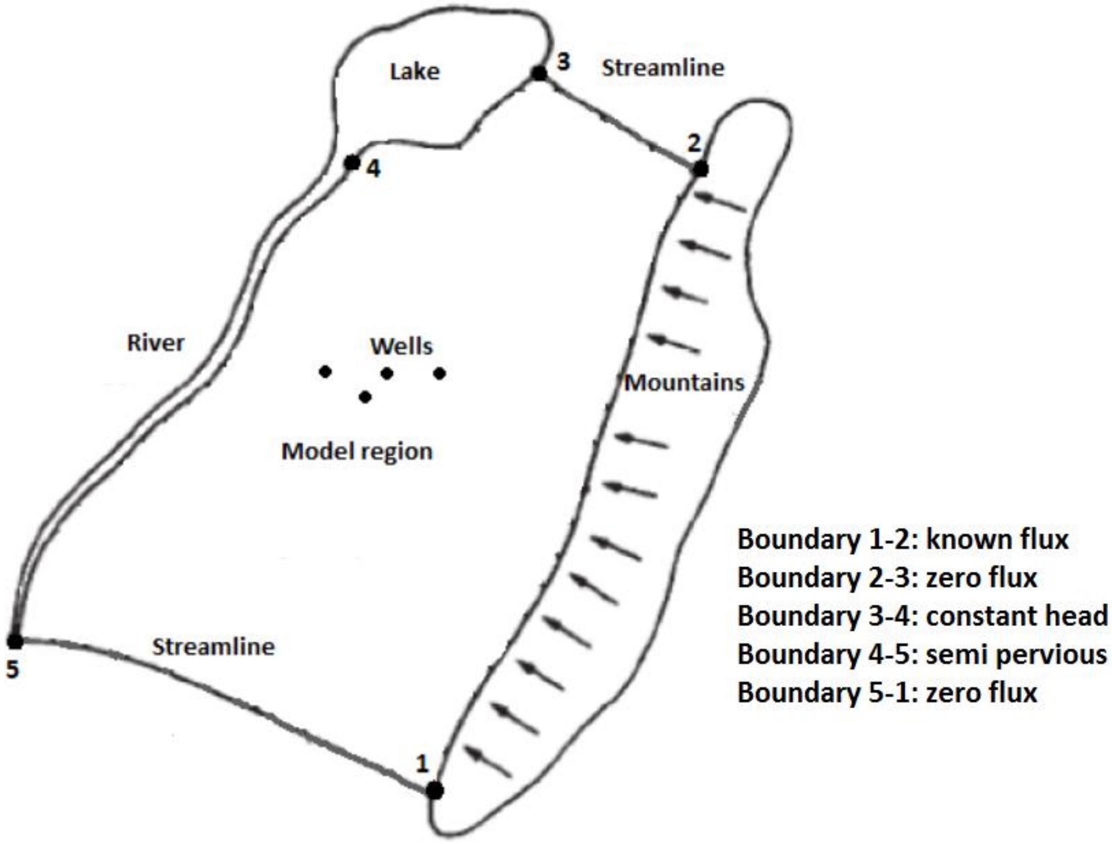


Figure 24: Representing the three main boundary conditions; The Dirichlet boundary conditions (constant head), Semipervious / mixed boundary conditions (known flux, zero flux) and Semipervious / mixed boundary conditions (semi pervious) (Modified Kinzelbach, 1986).

3.2.5. Calibration

To calibrating a model is to find the correct values of the different parameters in order to obtain a result from the model closest to the measured values from field. Normally a range of parameter values will be known from field observations, and can be used to restrict the possible outputs of calibration. There are two ways of calibration, manual and automatic. The manual method works by changing the input values by trial and error. The automatic calibration works by using numerical algorithms which gives back the best possible fit.

3.3. Hydraulic parameters

In this section the calculation of the different hydrological parameters are represented. The recharge is calculated from precipitation, and hydraulic conductivity from the grain size distribution curves.

3.3.1. Recharge

Recharge is the water in the unsaturated zone that moves downward and flows down into the saturated zone (Fitts, 2002). Recharge is calculated from the water balance, which is the input and the outputs of the groundwater system, where water is mainly brought into the system by precipitation. The recharge need to be calculated from the precipitation.

3.3.1.1. Theory

The water balance indicates that all water entering a region must either run through the region or be stored. The hydrological balance state it this way:

$$Flux\ in - Flux\ out = Rate\ of\ change\ in\ water\ stored$$

The water entering the area as precipitation evaporates, forms runoff or is stored (Fitts, 2002). The water balance is expressed as followed:

$$P = E + R + \Delta S$$

P: Precipitation

E: Evapotranspiration

R: Runoff

ΔS: change in storage

Evapotranspiration (E) is the evaporation, transpiration being the evaporation from vegetation (leaf and trunk) (Colleuille et.al, 2004). The temperature, air humidity, wind conditions, vegetation cover and soil moister affect the evapotranspiration (Roberts, 1983). The area studied in this study has little wind, and the ground is mostly fields covered by grass. In wet climate, such as the Norwegian climate, there in normally a higher water supply than evapotranspiration. This means that it is unlimited supply of water, and one get the concept of potential evapotranspiration (PET). This is the maximum amount of evapotranspiration that can occur in one area (Fitts, 2002).

The amount of runoff (R) infiltrating the ground or forming surface runoff is controlled by the topography, geology and the water saturation of the ground (already water filled pore space). The geology is affecting the permeability of the ground, high permeability results in high infiltration rate. The water that percolates all the way down to the groundwater is called groundwater recharge. Some of the infiltrated water will evaporate in the pores, and the roots of the vegetation will take up some water (Driscoll, 1986).

To find the evapotranspiration for the study area Tamm´s formula were used. Tamm´s formula is based on the assumption that radiation is the governing factor for evapotranspiration (Tamm, 1959):

$$E = 221{,}5 + 29T$$

E: evapotranspiration

T: temperature (^{o}C)

Recharge is then calculated as followed:

$$Recharge = P - E - R$$

Precipitation that infiltrates the ground become stored, evaporates or forms runoff. Factors controlling the evapotranspiration are temperature, humidity, wind and vegetation. Norway has a wet climate, leading to potential evapotranspiration being fulfilled (Fitts, 2002). The amount of runoff is influenced by the topography, geology and the saturation level of the ground. These factors affect the degree of infiltration of the runoff or surface runoff. Wet soil will lead to more runoff due to water-filled pores in the ground. The permeability of the soil or bedrock will affect the infiltration. Parts of the infiltrated water will evaporate in the unsaturated zone due to the air inside the pores, and the roots of the vegetation will take some up (Driscoll, 1986). Recharge is highest in areas with wet climate and permeable rock or soil type (Fitts, 2002).

3.3.2. Groundwater measurements

In order to collect continuous groundwater head data, Schlumberger divers was installed in the wells. The Diver is a data logger designed to do continuous pressure measurements. The diver consist of a pressure sensor designed to measure water pressure and atmospheric pressure, and a sensor to measure temperature. The diver measures the groundwater level by measuring both the pressure of the water column and the atmospheric pressure. A second diver is needed because of this to measure the atmospheric pressure. Only one diver is needed to measure the barometric pressure, unless the area is in the size range of several km (Schlumberger Water Services, 2014). In addition, the wells were measured manually at regular intervals (completed by Sweco).

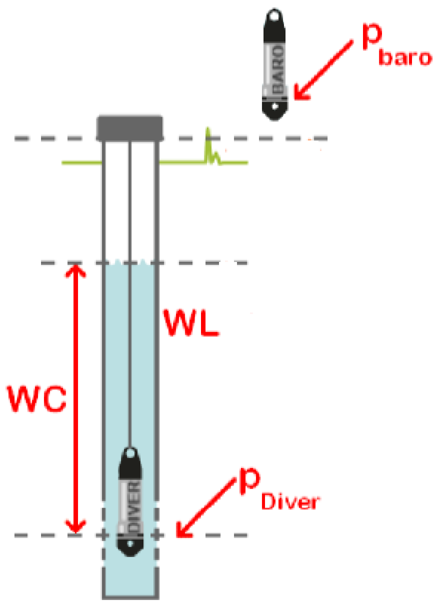


Figure 25: Showing the setup of divers in a well (modified Schlumberger Water Service, 2014).

In order to calculate groundwater level, manual measurements and diver measurements are needed from the same day. The diver in the well is measuring the water column above it and the atmospheric pressure (P) (fig. 25). To get the height from the diver to the top of the water column (WC) the calculation is as follows:

$$WC = P - ATM$$

3.3.3. Hydraulic conductivity

The grain size relates to the hydraulic conductivity, because the hydraulic conductivity depends on the pore size and the interconnection of the pores in the material. It is never very precise basing the hydraulic conductivity on the pore sizes, because the grain sizes is not giving information about the interconnections of the pores (Fitts, 2002). The grain size distribution curve is used to calculate hydraulic conductivity by the use of Hazen (1892) or Gustafsons (1986) modified Hazen (fig. 26). This will give some ranges of hydraulic conductivities to use for the calibration of the model. To use the Hazens method several requirements need to be met in relation to the grain size distribution (Colleuille, 2004). Because of the low sieving fraction, Gustafsons method was used. The results is represented in table 5. There is some uncertainties about the calculations of hydraulic conductivity, the grain size distribution curve is based on dry sieving, which increase the risk of fine material disappearing during the drying process. In general, the hydraulic conductivity is most likely varying because of deposition under different conditions, such as variation in riverbed and flow.

Gustafsson method (1986):

$$U = \frac{d_{60}}{d_{10}}$$

d_{10}: grain size corresponding to weight percent of 10%

d_{60}: grain size corresponding to weight percent of 60%

$$e = 0.8 * \left(\frac{1}{2lnU} - \frac{1}{U^2 - 1}\right)$$

$$g(U) = \frac{1.3}{\log(U)} * \frac{U^2 - 1}{U^{1.8}}$$

$$E(U) = 10.2 * 10^6 * \frac{e^3}{1 + e} * \frac{1}{g^2(U)}$$

$$Ks = E(U) * (d_{10})^2$$

K_s: hydraulic conductivity (Andersson et al. 1984)

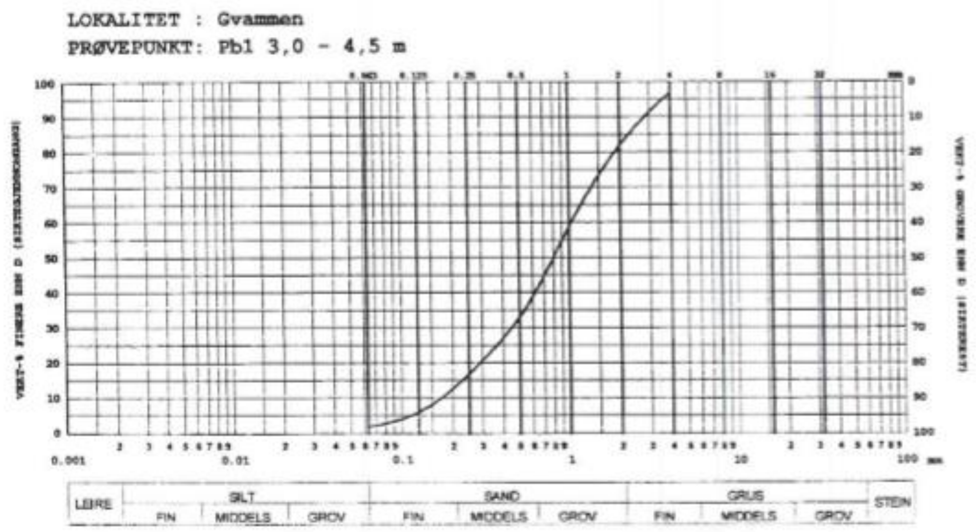


Figure 26: Grain size distribution curve, giving d_{10} and d_{60} This curve is from well 1 from 3-4,5 meters depth.

4. Results

4.1. Statistical analyses

Statistical analyses is applied to compare the different properties of the aquifers and to know how the aquifers react to hydrological changes like precipitation, modification of the level of the lake and river flow modification. The correlation and cross correlation will establish links between the different hydrological parameters within the aquifer like the rivers connection to upper and lower aquifer, and the connection between the river and the lake. The cross correlation will give a lag in days between the change in the hydrological conditions and the effect over the aquifer.

4.1.1. Correlation

Correlation is a form of time series analyses provides a good insight into of changes coupled or not in the upper aquifer and lower aquifer (Larocque et.al., 1998). This provides the interrelation with the aquifer and the hydrological parameters. The analyzes giving a cross-correlation value of +/- 0,3 or more/ less is indicating a form of relationship, while the values lower/higher than +/- 0,3 is concluded to have no relationship (Dancey and Reidy (2004)).

The correlation between the coupled wells in the lower and upper aquifer shows high correlations (between 0.8995 (Pb99 and 0.5402 (Pb15)) (fig27). Well 11, 12 and 15 are showing more or less the same correlation trends while well 9 is a bit higher. Well 9 is placed outside the area which the organic layer is assumed to cover.

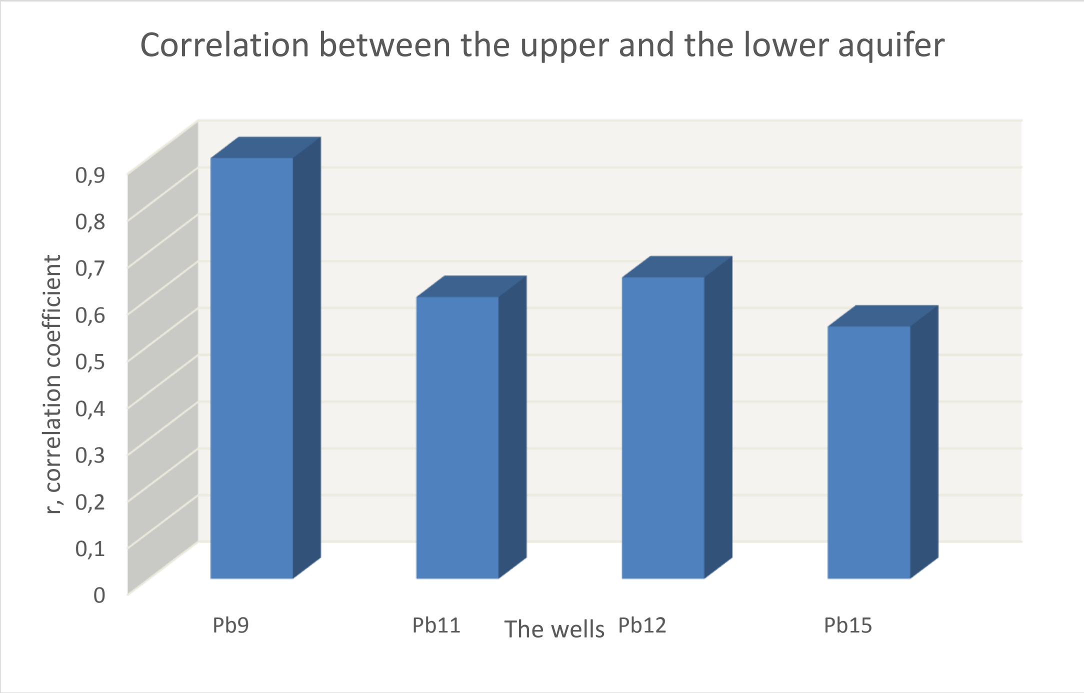


Figure 27: Showing the correlation between the upper and lower aquifer at the different wells.

In order to study the impact of precipitation at the lake water level correlation between the lake and the precipitation (fig. 28) were carried out. The flow in the river from the power plant to the lake were also correlated with the lake. Both factors shows low correlation to the level of the lake, indicating little impact on the lake level.

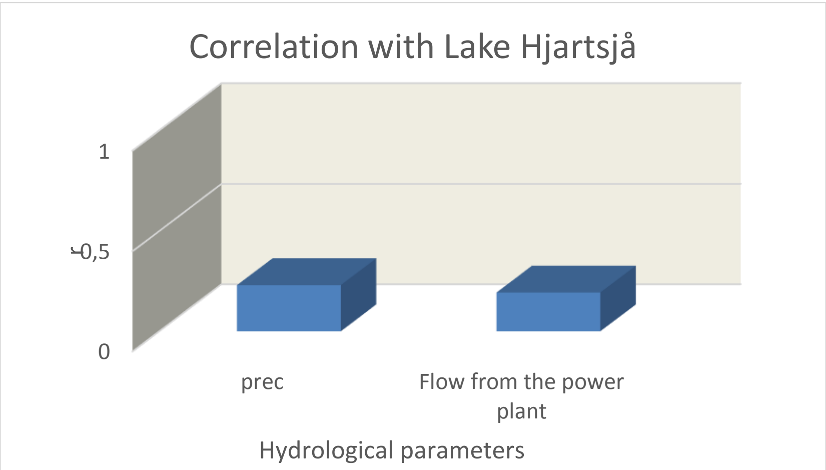


Figure 28: Correlation between the lake and precipitation and the lake and the flow from the power plant.

The different wells in the upper- and lower aquifer are correlated towards the lake (fig. 29). The correlation is giving an immediate difference between the upper and lower aquifer. The upper aquifer is in general giving high correlation values, while the lower aquifer is giving low correlation values. The upper aquifer is interacting with the lake, and the highest correlation value is in well 15, which is also the well closest to the lake

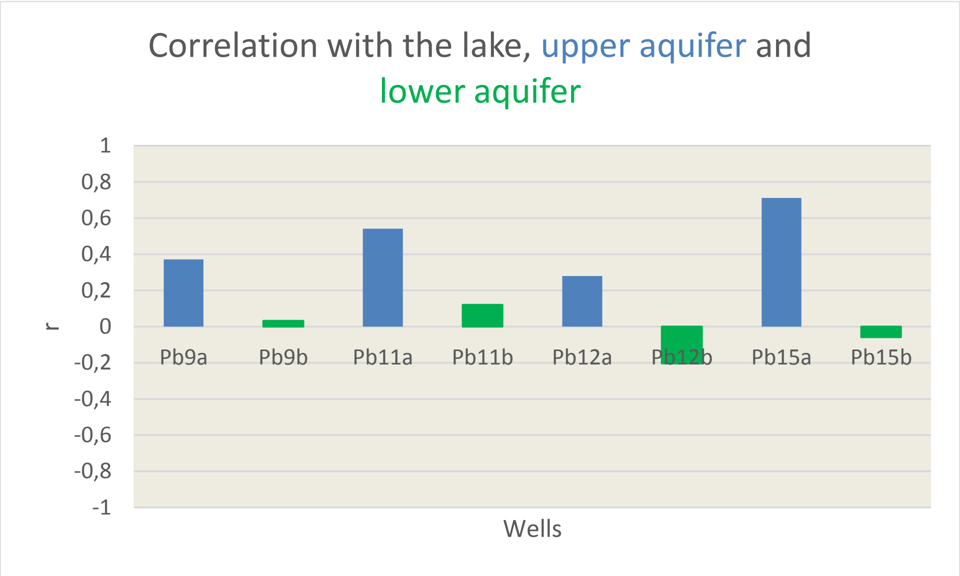


Figure 29: The correlation between the lake and the upper aquifer, and the lake and the lower aquifer.

The correlation of the recharge and the upper- and lower aquifer shows low correlation, not having impact on the lake level (fig. 30).

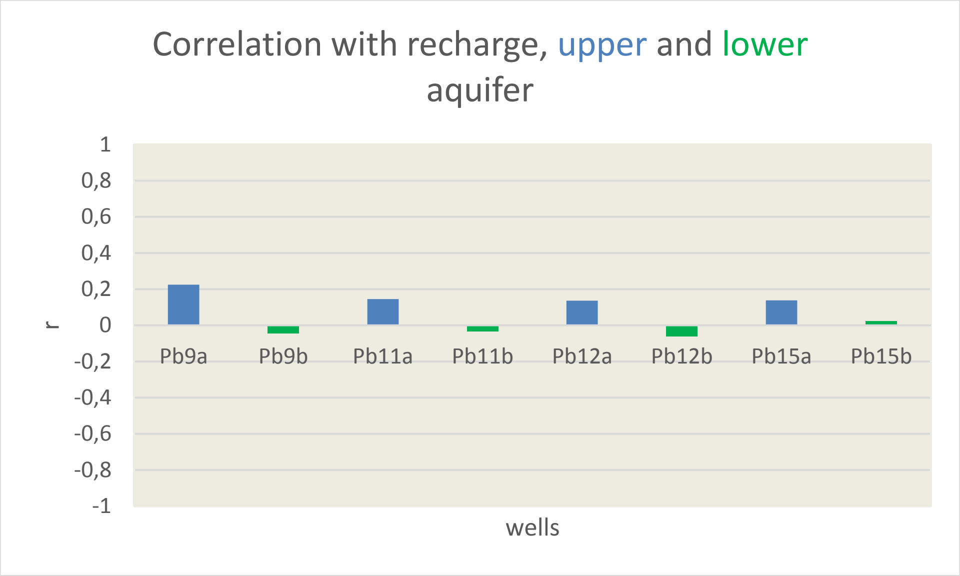


Figure 30: the correlation between the recharge and the upper and lower aquifer.

The correlation between the river and the upper- and lower aquifer (fig. 31) is in general showing a high correlation for both upper and lower aquifer. The upper aquifer is showing a bit higher correlation than the lower aquifer. The highest correlation is in well 12, next to the river, but well nine is also placed next to the river further west than well 12. Well 12 also show a big difference in the correlation with the river in the upper aquifer, and the correlation with the river and the lower aquifer; it actually does have the highest correlation in the upper aquifer and the lowest correlation in the lower aquifer. Well 9, which is also placed close to the river, has a high correlation in both upper- and lower aquifer.

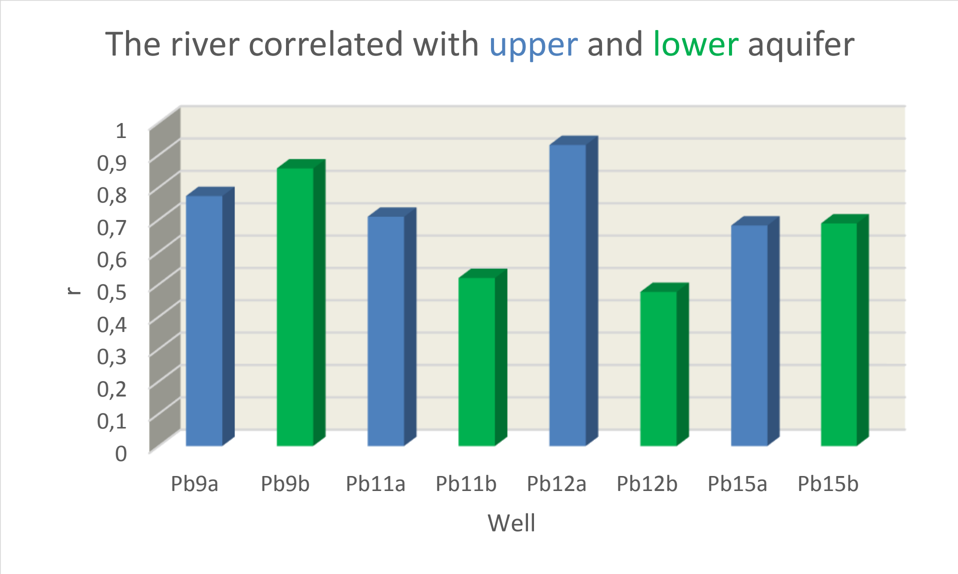


Figure 31: The correlation between the river and the upper and lower aquifer.

The correlation between the flow proceeding from the power plant and the upper aquifer and the river and the lower aquifer. There is in general low correlation between the river and both the upper and lower aquifer (fig. 32). The only well, which is showing a significant correlation, is well 12b. The closest well to the river is well 11, and it is not showing a correlation.

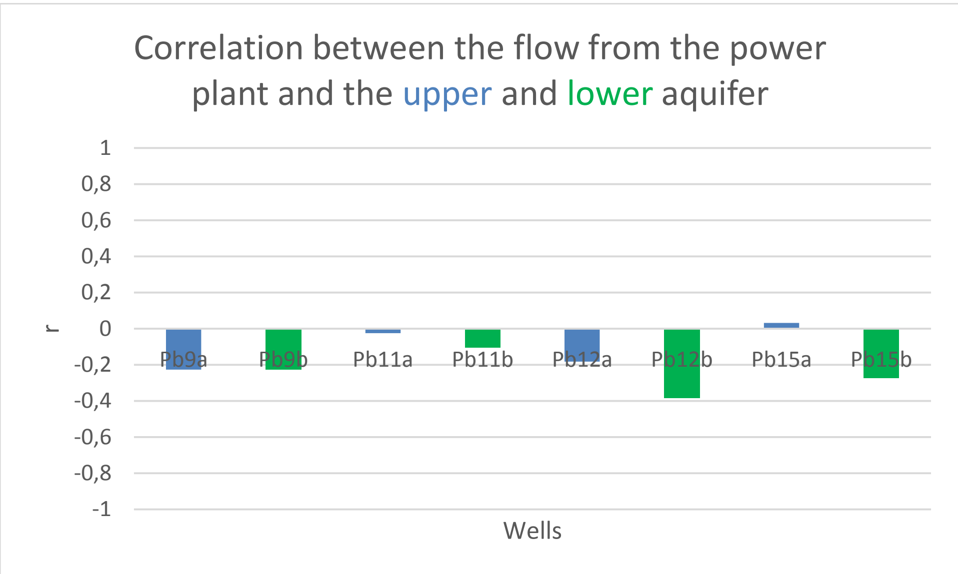


Figure 32: Correlation between the river coming from the power plant, and the upper and lower aquifer.

4.1.2. Cross correlation

To identify the time gap between the hydraulic heads within the aquifer, and hydrological parameters (i.e. rivers, precipitation and lake) cross correlation functions of these variables were analyzed.

The cross-correlation between the upper and lower aquifer are represented in figure 33, and shows daily water fluctuations. The upper aquifer (a) were considered an input, and the lower aquifer (b) an output. The cross-correlation function shows the response in the heads of the lower aquifer, when the heads in the upper aquifer changes. Based on these wells there are no lag between the upper- and lower aquifer.

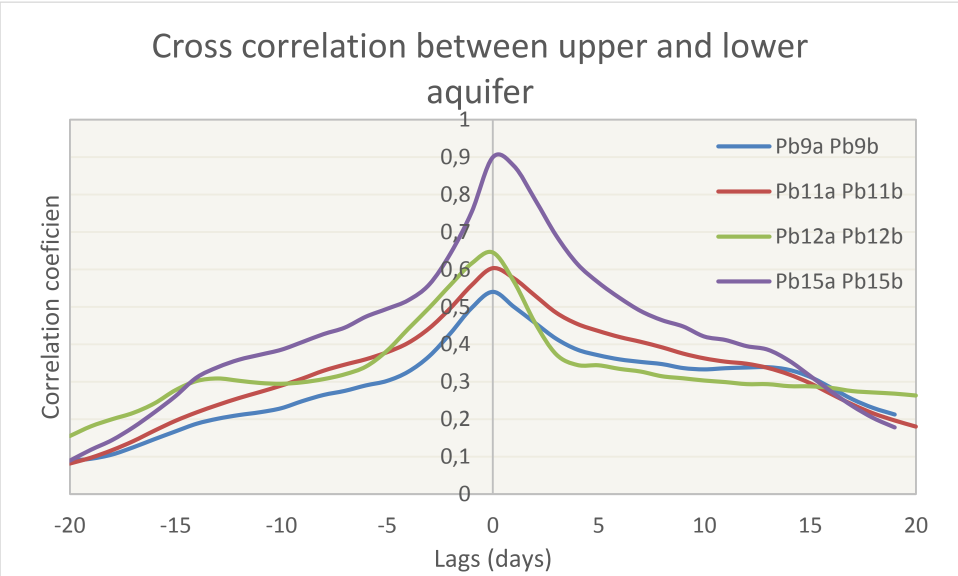
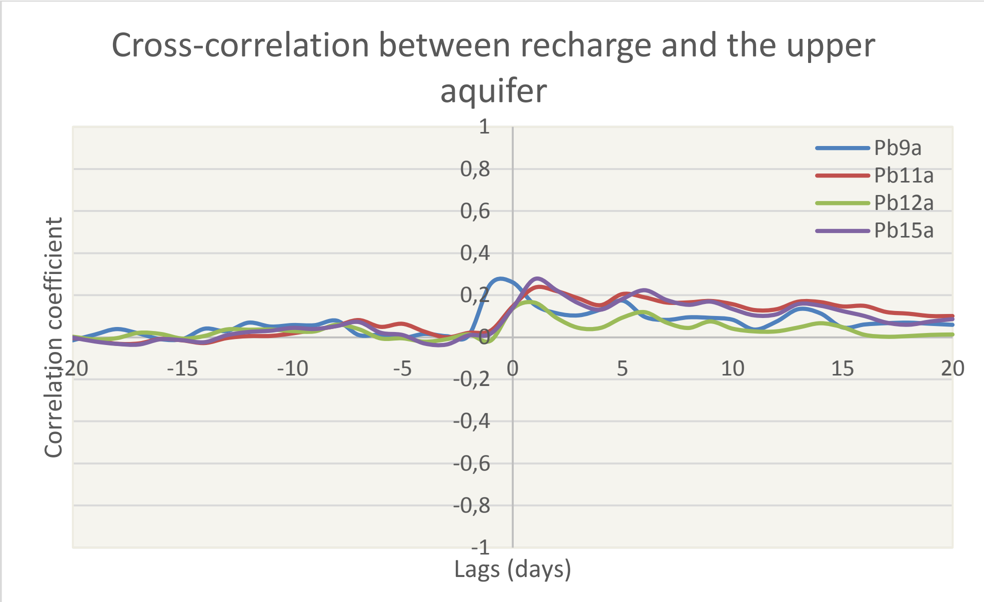


Figure 33: The cross correlation between the upper and lower aquifer.

The relationship between recharge and the upper aquifer, and recharge and the lower aquifer are represented in figure 34. The result is giving the response in heads of the upper and lower aquifer with the change in recharge. Well 11 and 15 is showing a lag of 1 for upper and lower aquifer. Well 9 is showing a lag of -1 in the upper aquifer.



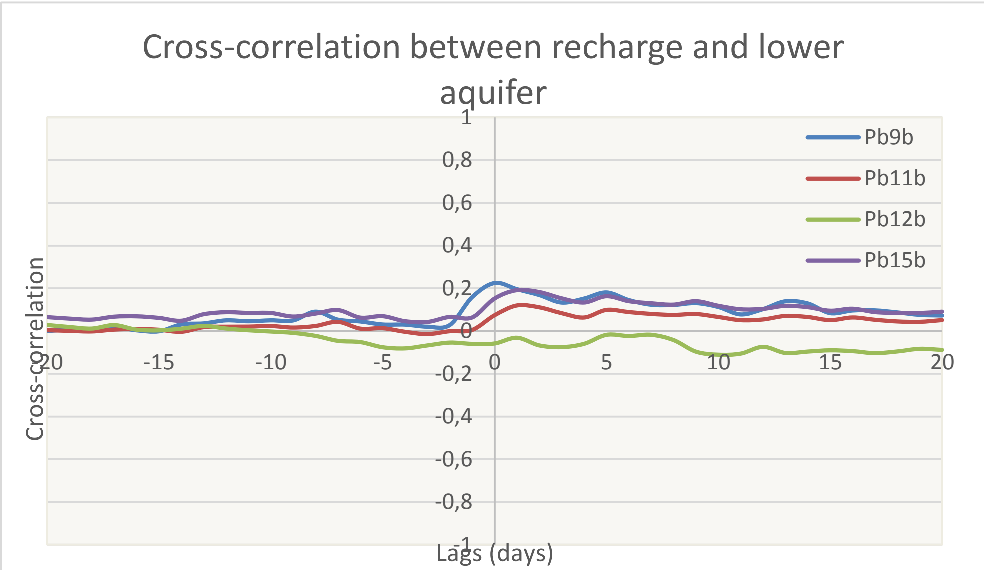
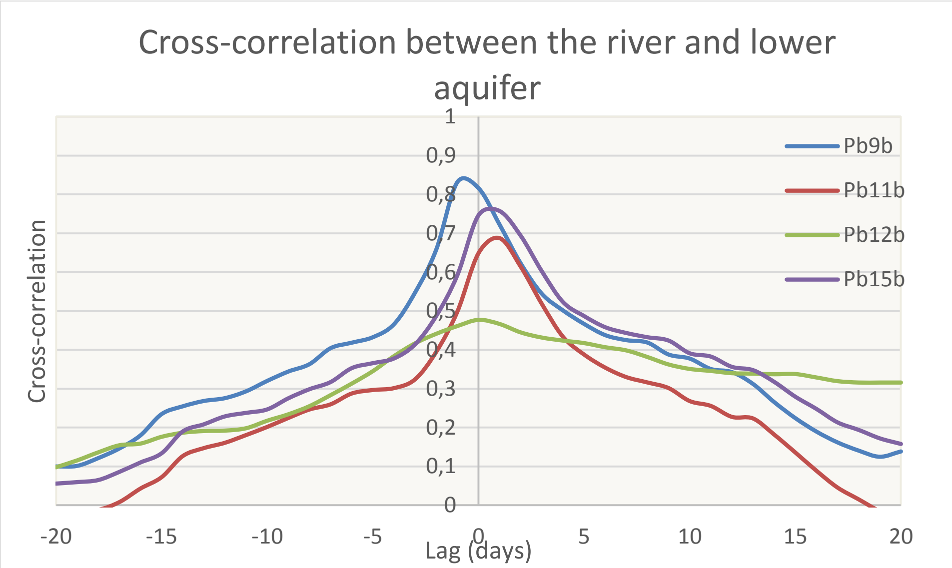


Figure 34: The graph at the top is showing a cross-correlation between recharge and the upper aquifer, while the graph at the bottom is giving the cross-correlation between the recharge and the lower aquifer.

Figure 35 is representing the cross-correlation between the daily water fluctuations in the river, Hjartdøla and the upper aquifer, and the daily water fluctuations in the river and the lower aquifer. The head in the river is the input, and the heads of the upper- and lower aquifer is the output. This gives a reaction in the upper- and lower aquifers based on changes of the level in the river (fig. 35). Well nine is showing a lag of -1 in both upper and lower aquifer. Well 11 is showing a lag of 1 in both aquifer, while well 15 is showing a lag in the lower aquifer but not the upper aquifer.



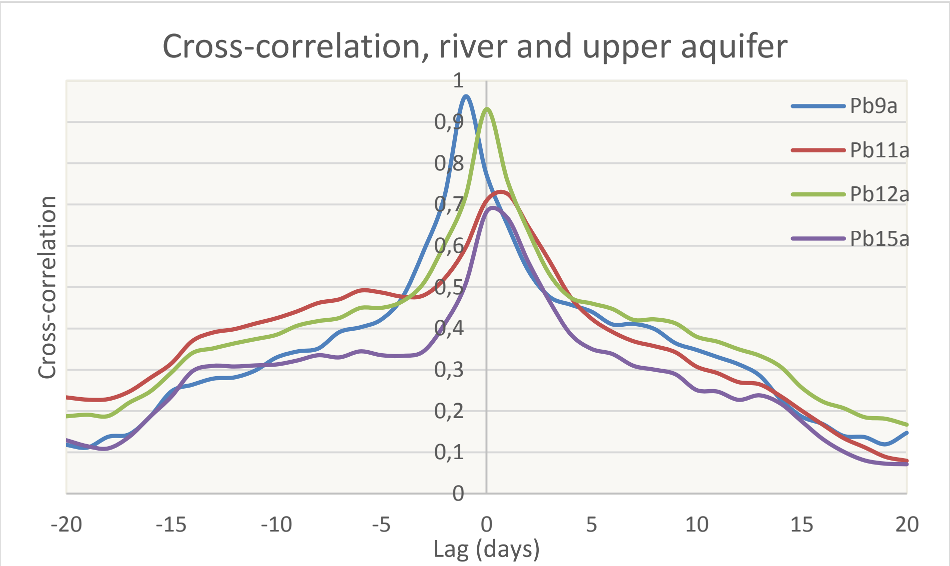


Figure 35: The cross-correlation between recharge and upper aquifer (in the graph on the top), and lower aquifer (at the bottom).

Figure 36 is representing the cross-correlation function of daily water fluctuations in the lake and heads of the upper and lower aquifer. The input is the lake, and the output are the heads in the upper- and lower aquifer. The correlogram (the graph) show differences in response to the lake and the upper- and lower aquifer. Well 9 which is placed furthest away from the aquifer show a lag of -1, otherwise there are no lags in the upper- and lower aquifer.

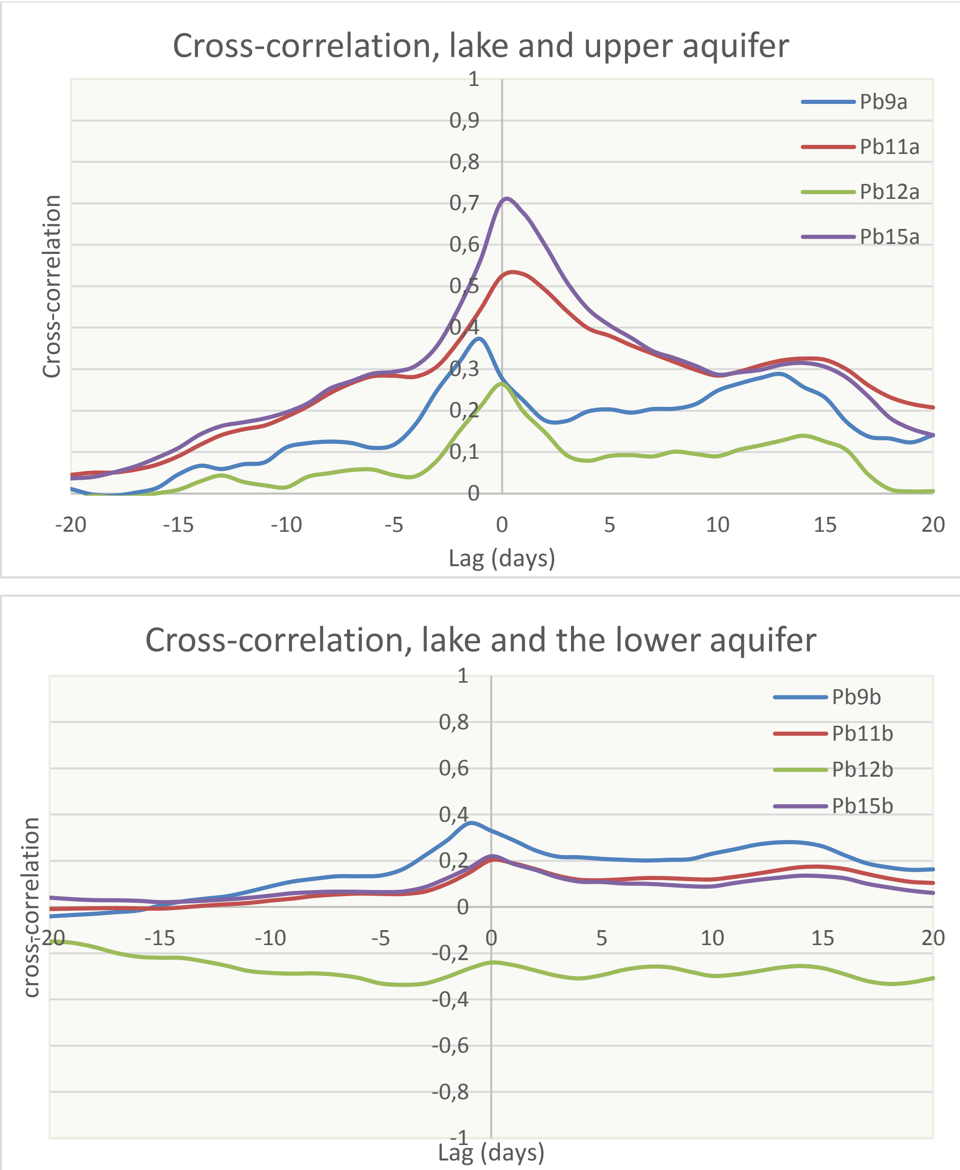


Figure 36: The cross-correlation between the lake and the upper and lower aquifer.

The cross-correlation between the lake and the different hydrological parameters (i.e. precipitation, the lake and the river, and the lake and the river from the power plant) is represented in figure 37. This cross-correlation were conducted in order to distinguish which parameters had a lag.

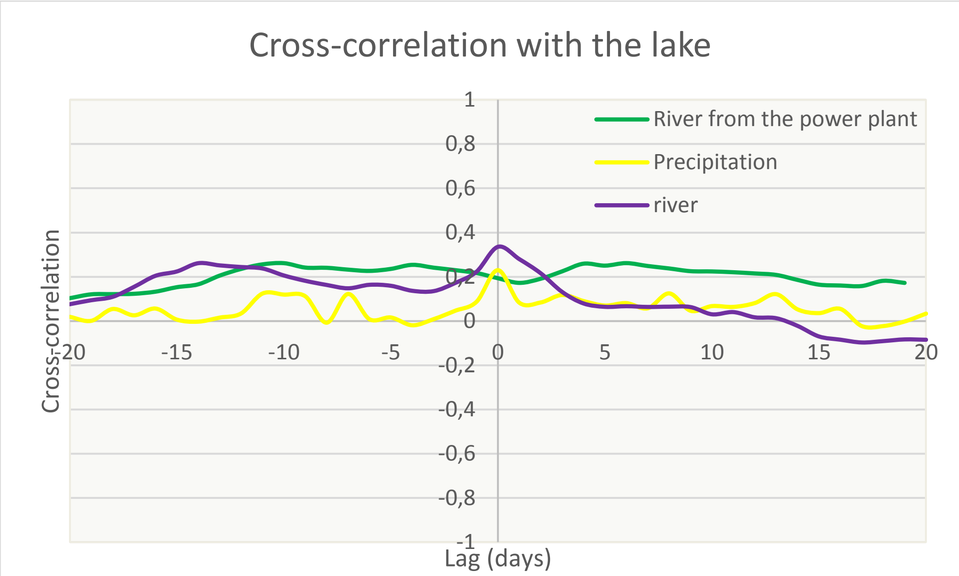
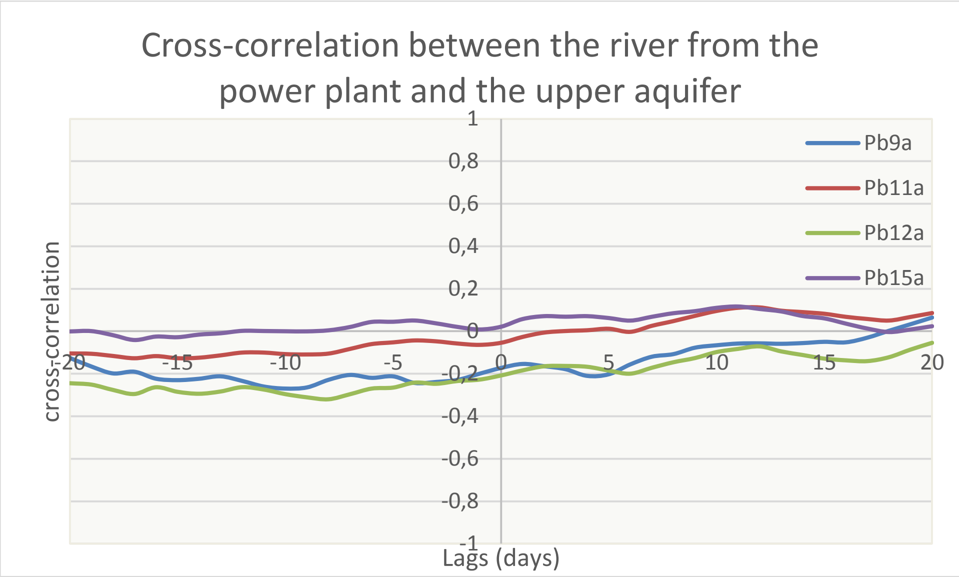


Figure 37: The cross-correlation between the lake and the different hydrological parameters affecting it.

The cross-correlation between the river from the power plant and the upper- and lower aquifer is showing no lag (fig. 38).



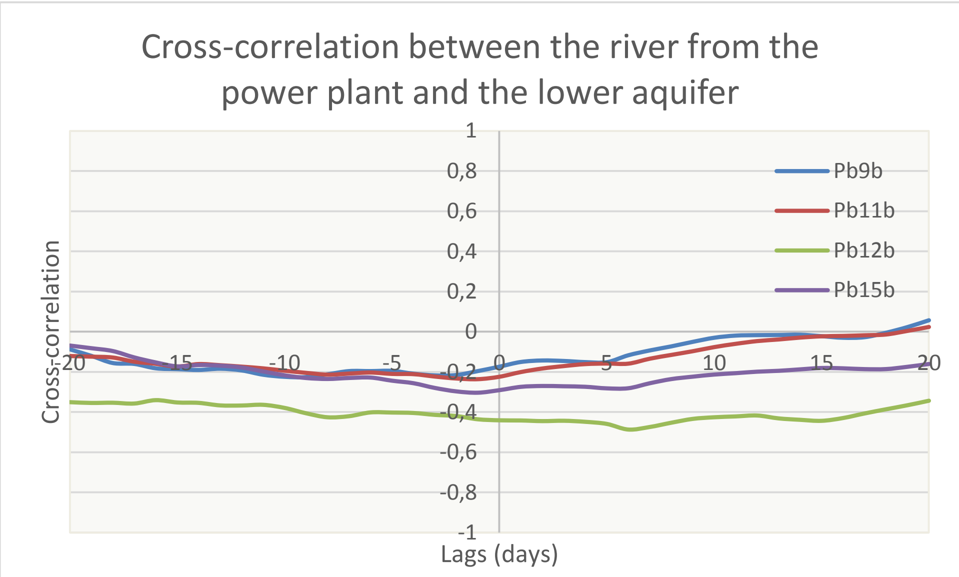


Figure 38: The cross-correlation between the river from the power plant and the upper and lower aquifer.

4.2. Numerical modeling

A multi aquifer model were constructed. In order to look at the impact of the unknown factors, such as the length of the organic layer, a simple model of the profile of the aquifer were made. This model worked as a test to decide the different characteristics of the main model.

4.2.1. Model extent

The model extent was established mostly based on the shape of the valley. The aquifer is placed in a valley, where the sides are covered by vegetation. This makes it difficult knowing where the aquifer stops, and the bedrock starts. The boundary of the model was therefore chosen to follow the topography, on the border between the flat valley plain and the steeper valley sides (fig. 39). In east direction is the model bordering to the lake, and the river in the northeast corner. The boarder in the west side of the valley was placed where the valley narrows in. The depth of the aquifer is unknown, and was in this model put to 50 meters, following the same topography as the top.

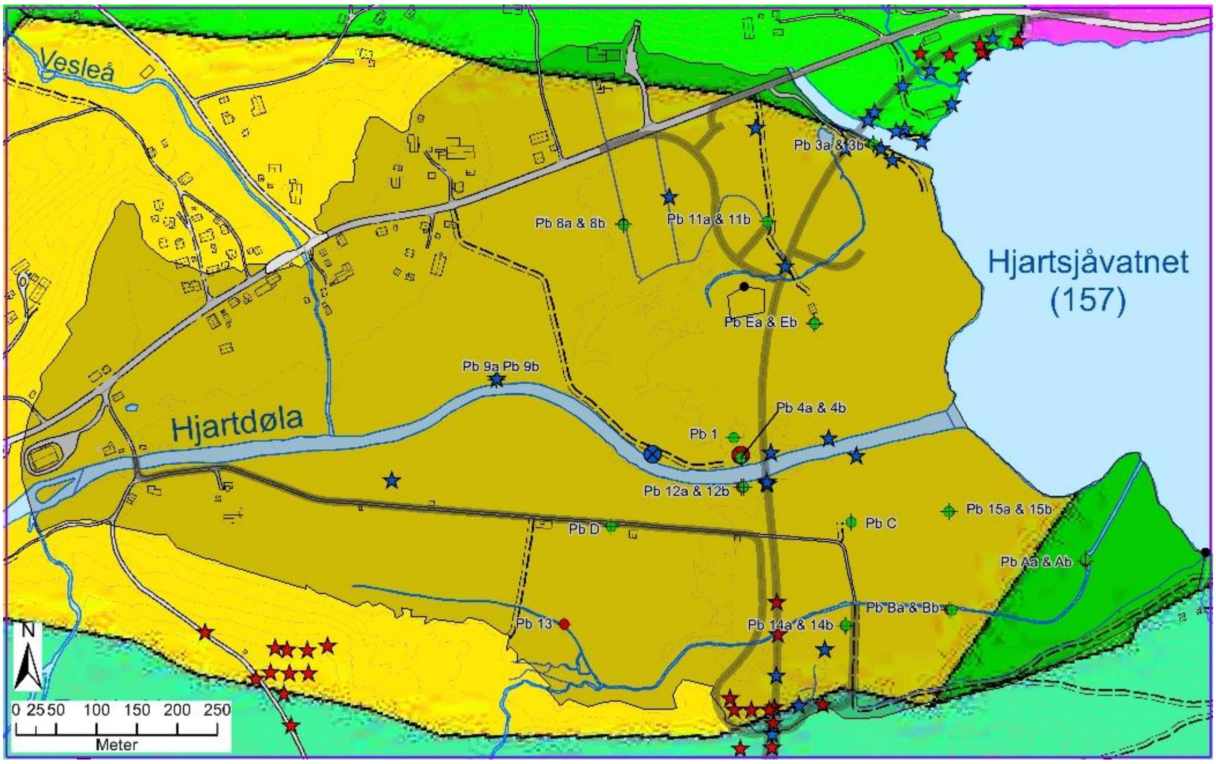


Figure 39: The extent of the model is cover by the dark area.

4.2.2. Model geometry

The model geometry was based on the sediment cores and the pressure head data from the wells. Since the upper layer and the organic layer is having variations in thickness, a scatter plot was made based on the sediment logs and a topographic map, in order to create the three layers.

The dilution of the mid layer until it disappeared was fixed by making the mid layer so thin that it did not have any big impact on the flow in the model. The scatter point was then interpolated to 3D grid. Because of the interpolation is there small differences in the topography in the map, and the real topography (fig. 40 and 41)(table 7). It is a multiple aquifer consisting of 3 layers, where the middle layer dilutes towards west.

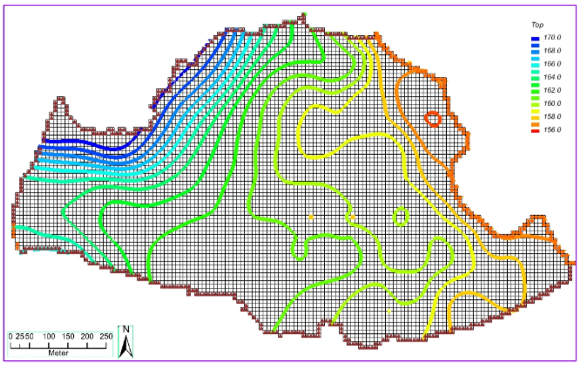


Figure 40: The topographical map of the model. 1 meter equidistance.

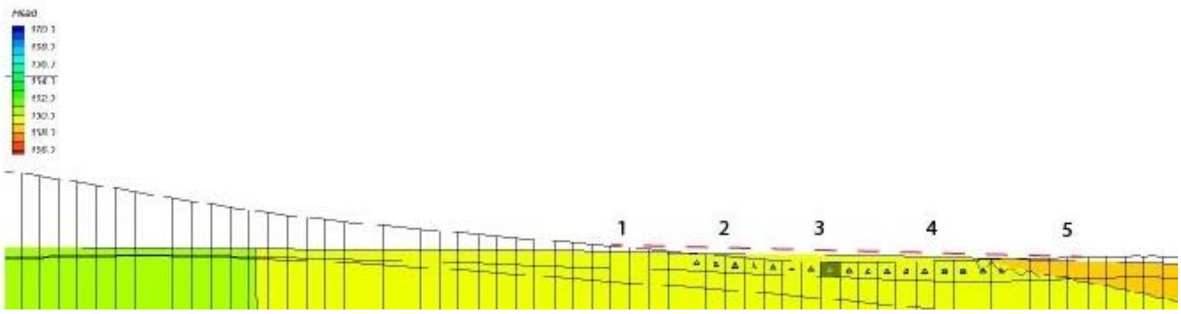


Figure 41: Problems with the model being flooded, but the flooding was only by cm above the ground.

Table 7: The difference in the topography from the model to the map.

Point in fig. 14	Top elevation model (m)	Head (m)	Elevation map (m)
1	160.34	160.1	160.1
2	159.7	159.7	160.4

3	158.8	158.8	160
4	158.45	158.45	160
5	158.85	158.85	159.7

4.2.3 Model boundary conditions

The modelled area has a steep valley side south of the area, and a gentler slope on the north side. The recharge from the catchment area is entering the aquifer in four ways:

1) Water entering the aquifer from the lake bordering to the modelled area
2) Water leaking through the fractured bedrock (fig. 42), or as surface water flowing down the steep mountain sides in creeks
3) Water flowing into the valley upstream of the modelled area, and then flowing through the sediments in the valley
4) Entering the aquifer through the river.

Figure 42: The fractured quartzite at Gvamsletta. The darker spots show the wet areas from water leaking out through fractures.

External boundaries: The general head boundary is used for the north and south side with the valley slopes and the fractured quartzite. Constant head boundary is used for the lake and the west side where the boarders are in the valley bottom.

Internal boundaries: There are two streams modeled in the area, one is the river Hjartdøla that flows through the whole area, and one is the creek on the south side. There is also a drain on the northeast side (fig 43).

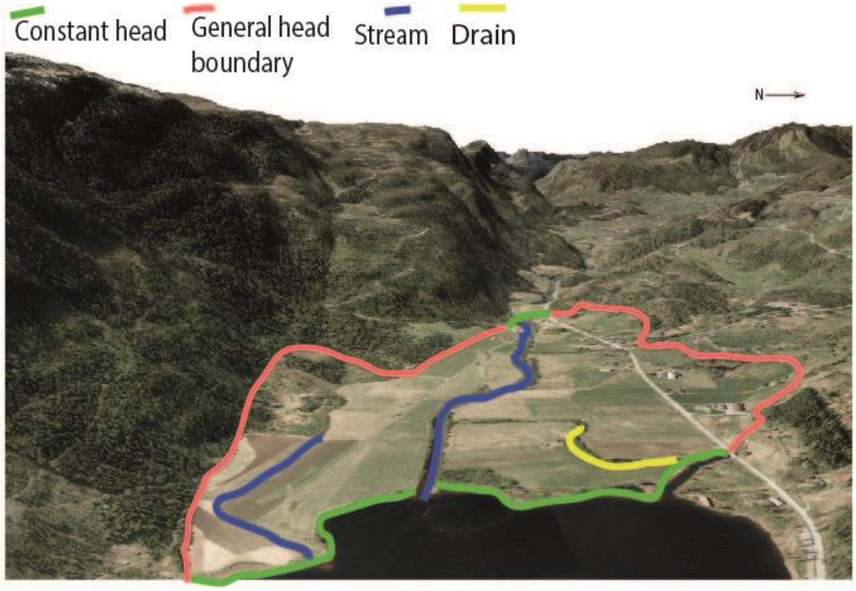


Figure 43: The boundary conditions represented in the model.

The recharge were calculated from the average of the monthly precipitation and the average of the evapotranspiration for all the years. The result were then the average recharge: 0.00145 m/d. It is assumed that 100 % of the runoff will infiltrate and form recharge. This is due to the flat terrain and the poor sorting of sediments.

4.2.3. 2D Modell

A model were made of the cross section of the aquifer (fig. 44). It is a model made before the 3D model in order to look at the impact of the different unknown factors of the model. Different scenarios were tried out in order to look at the impact on the computed heads. The boundaries at the side (representing the west side of the aquifer) had constant head, and the other side by the lake had the constant head in the upper layer, but not in the lower layers. The reason for this being the lower aquifer most likely continues underneath the lake.

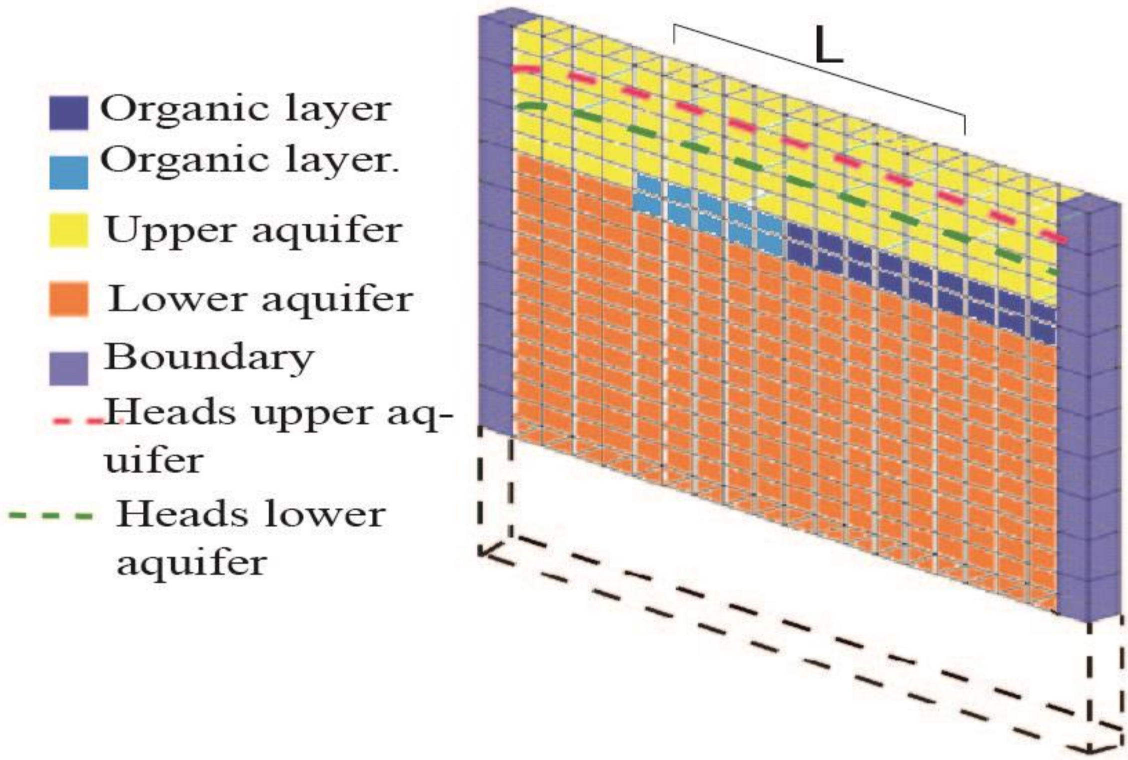


Figure 44: Illustration of the model of the cross section.

The exact length of the organic layer is not known, it is built on approximations. The 2D model were used to look at the impact on the computed heads when changing between long and short organic layer. A short organic layer is giving a lower computed heads in the lower aquifer, than a long organic layer. In the upper aquifer is it the opposite. The short organic layer is giving a higher computed heads than the long organic layer (fig. 45).

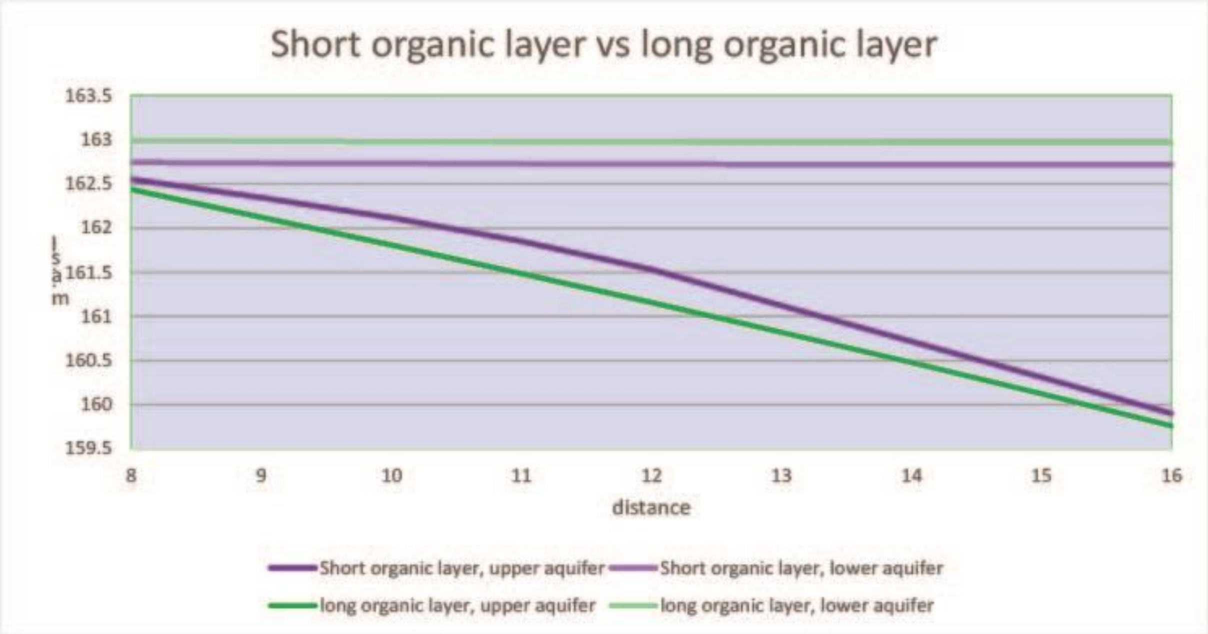


Figure 45: Showing the impact on the calculated heads when there is a long organic layer, and when there is a shorter organic layer.

The impact of the depth of the lower aquifer is giving a much smaller difference in computed heads. The lower aquifer is not showing any difference at all, while the upper aquifer shows a minor difference (fig. 46).

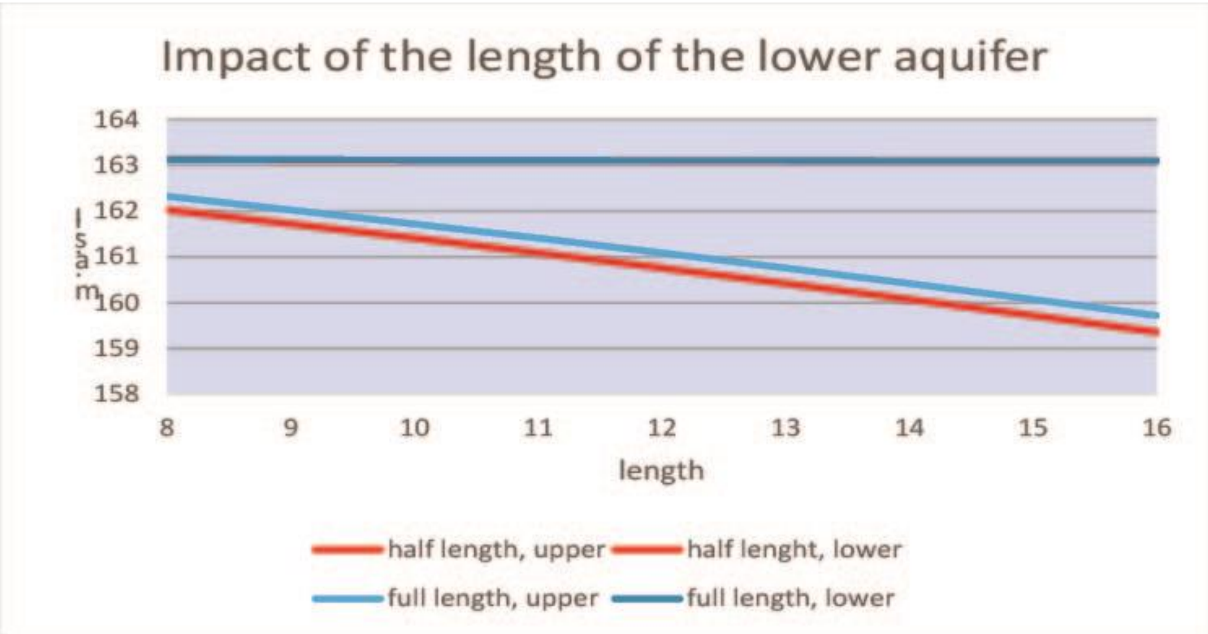


Figure 46: The impact of the calculated heads on a deep lower aquifer, and a shallow lower aquifer.

4.2.4. 3D Model

A steady state 3D model were constructed based on the input values in table 2. Calculated from the lake measurements the lake level were on average right under 157 meters, and the standard head bordering to the lake were set to 156.5. Layer 2 and 3 did not have any boarders towards the lake. This is because the organic layer and the lower aquifer is believed to continue underneath the lake. The constant head in the valley, where the river enters the modelled area, was set to 159 and 160. This was found by calibration. The same constant head was chosen for all the 3 layers. The general head was decided by the calibration. The hydraulic conductivity were based on the results from the grain size distribution curve. In layer 3, the part underneath the organic layer were chosen to have a high hydraulic conductivity in order to simulate the artisan pressure. The hydraulic conductivity were then decrease from the end of the organic layer and westward. The conductance for the river and the creek was calculated based on the area of the river, the length and the hydraulic conductivity in the riverbed. There was some problems with flooded and dried cells. This is most likely because of the thin upper layer, with an impermeable layer underneath. This made the model sensitive to any changes before cells went dry or got flooded.

Table 8: The input values used for constructing the 3D-model.

	Layer		
	1	2	3
Constant head lake	156.5		
Constant head, west	159	160	160
General head	158-161	160	160
Drain (m^2/d) (m)	0.1		
Stream, river	0.432/0.2		
Stream creek	0.2		
New production well (m^3/d)			-288
Old production well (m^3/d)			-192

recharge (m/d)			0.00145
Hydraulic conductivity (m/day)	6-30	0.03-2	50-100
Anisotropy	10	10	10

The hydraulic heads calculated from the steady state is displayed in figure 47. On can see from the model that the lower aquifer in general has higher heads than the upper aquifer, and the heads towards the east is the same. The flow is towards the lake, and the flow is more or less perpendicular to the lake. In the organic layer and in the lower aquifer the flow is gradually turning more towards the southeast end of the modelled area. The water table distribution suggest no gradient from the river to the aquifer.

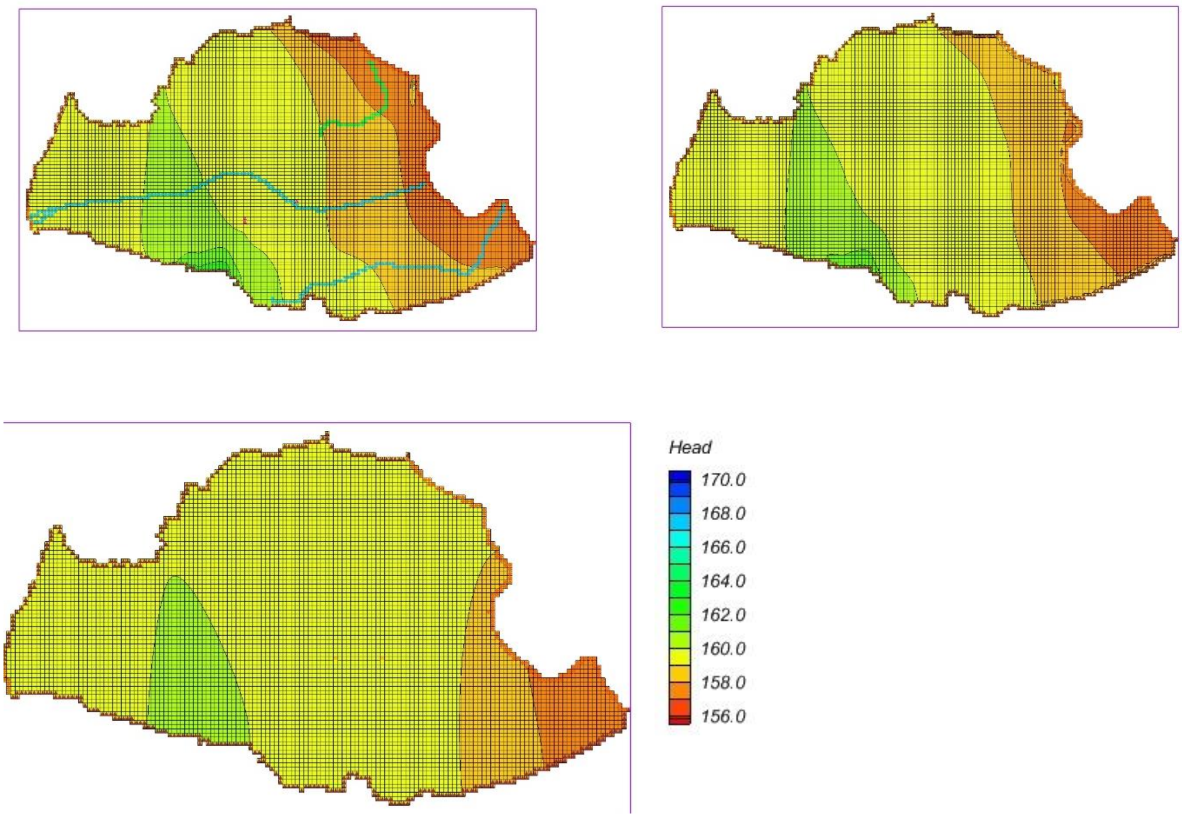


Figure 47: The hydraulic heads in the 3 different layers of the model. Layer 1 up left, layer 2 up right and layer 3 down left.

The flow budget is presented in figure 48. The recharge of the aquifer is the general head boundaries, the recharge and the stream leakage. The wells and the drains is only discharge, where the wells has the highest discharge (-768 m^3/d unlike -6.23 m^3/d). The constant head is the highest discharge of the area (recharge-discharge = -10582 m^3/d). The highest recharge is from the general head boundaries. By studying the flow budget, constant head is the parameter affecting the aquifer the most.

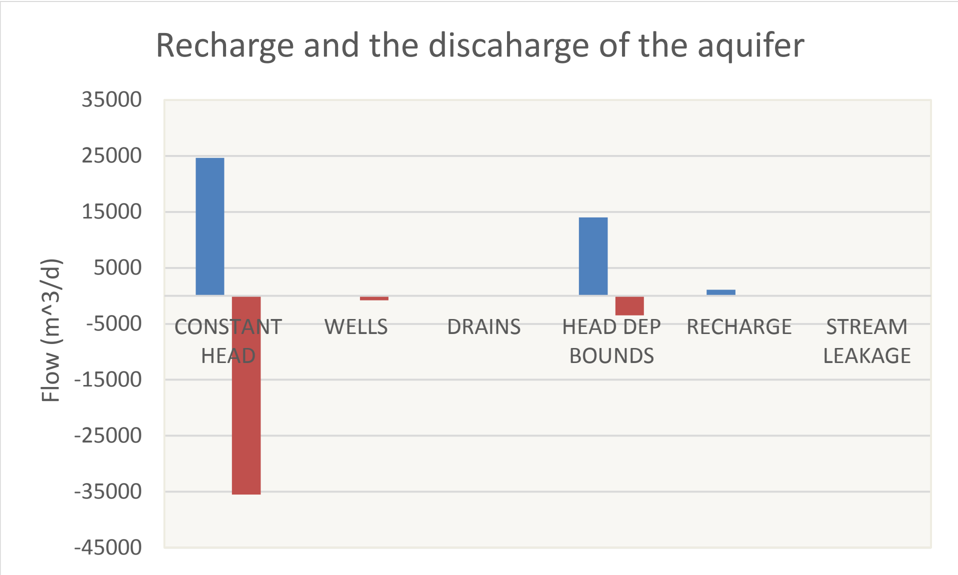


Figure 48: The flow budget of the aquifer.

4.2.4.1. Calibration

During the calibration process the parameters horizontal hydraulic conductivity, general head and constant head were modified in order to obtain a better match with the water table observations. The range of values used for hydraulic conductivity are the values found in the grain size analyses (table 1). The calibration process were evaluated by comparing to the general head of 16 different wells, where the heads used were the average of all the measurements for each well. It was ten wells for the lower aquifer and 6 for the upper aquifer. During the calibration process the parameters horizontal hydraulic conductivity, general head and constant head were modified in order to obtain a better match with the water table observations.

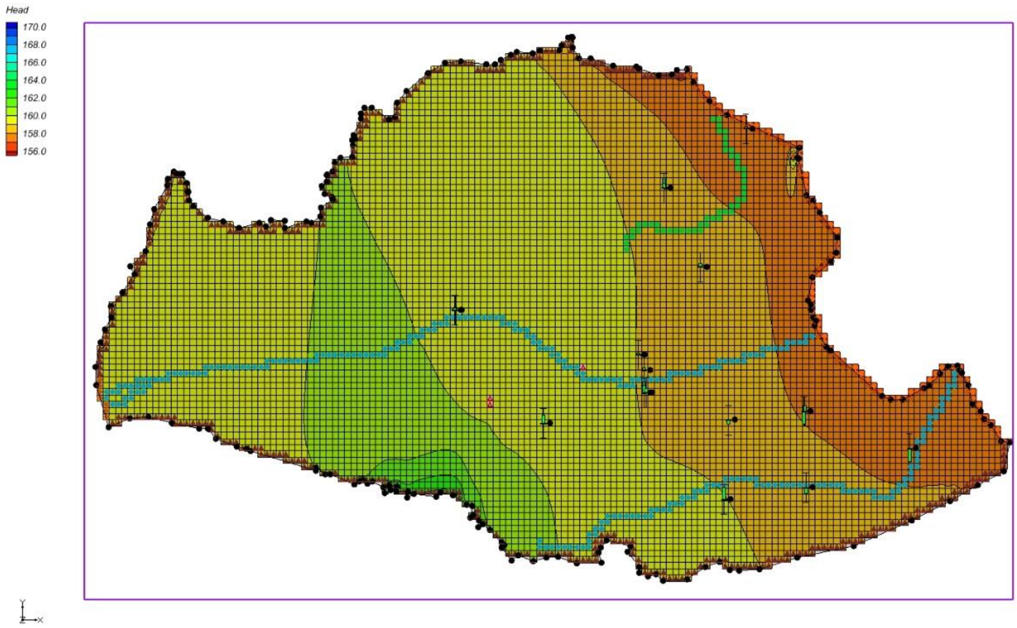


Figure 49: The obeservation wells used for the calibration.

The calibration outcome was evaluated through comparing computed vs observed heads. The model gave small or almost no changes in the observed vs calibrated heads when changing the hydraulic conductivity. The model was most sensitive to changes in constant head, and then the general head. It was some problems finding a good calibration without having big parts of the model dry and flooded (they mostly accrued both at once). The R^2, which is a measurement of how well the points fit a linear line, is at 0,574. This is not a very good fit. The Root Mean squared error (RMS) is the most common model error statistic used to verify that a model is correctly calibrated (fig. 50). Smaller error value indicate better calibration. The value vas 0.9.

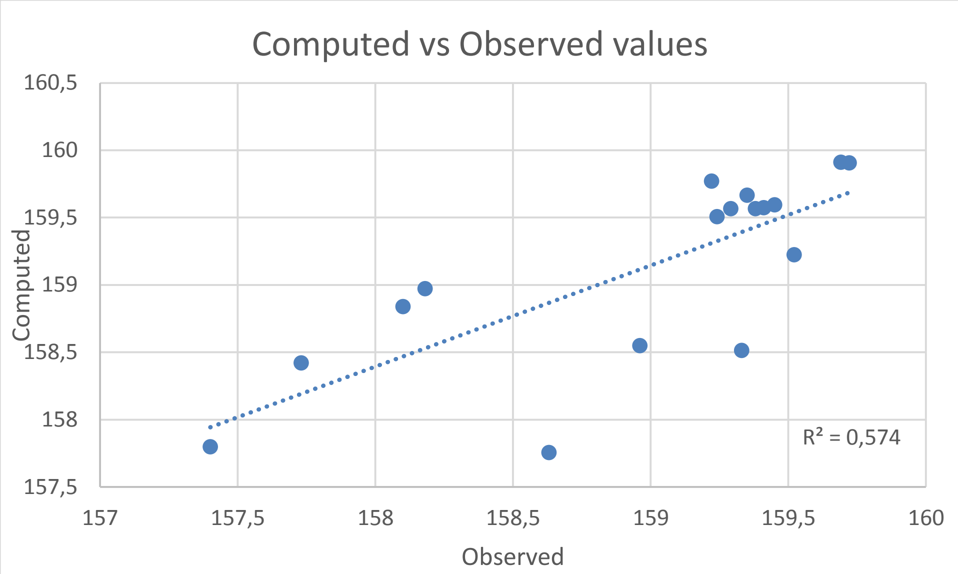


Figure 50: The values whit computed vs observed heads.

4.2.4.2. Particle transportation

Particle transport was used in order to look at the effect of a potential accident, what will happen if an oil spill occurred along the road? By studying the sediment cores there was found a higher hydraulic conductivity in the organic layer around well 1 and 2. This is right by the drinking water well. The hydraulic conductivity in the organic layer was 4.43E-04 m/s, compared to 3,8E-07 m/s and 6,4E-07 m/s. At well 1 is the hydraulic conductivity higher in the organic layer then the upper aquifer.

Oil spill scenarios was constructed by using particle transport. First at the north side of the area with high hydraulic conductivity (fig 51). One can see from figure that the particles do not go true the organic layer. Then at the south side of the river. In the end the horizontal hydraulic conductivity was put set to 60 in order to see if the particles penetrated true. Figure 28 shows that the particles penetrate into the organic layer, but not true it.

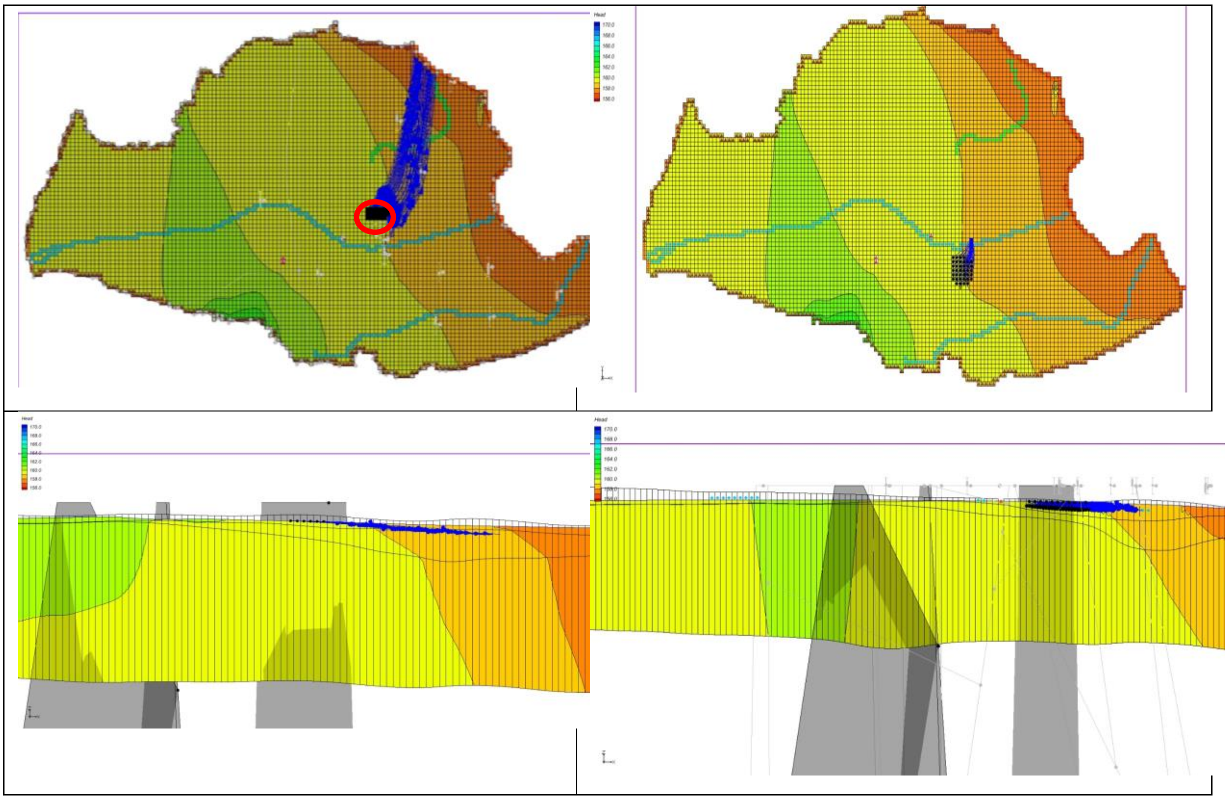


Figure 51: The diffrent particle transport scenarios is represented. Upper left conrenr is over the high hydraulic conductivity. Right is on the south side of the river. The one down at the left side is with a vertical hydraulic conductivity of 60 m/d. The one at the right is the same as at the upper left corner.

5. Discussion

Within this chapter a discussion of the data acquired follows. Some of the points discussed are statistical analyses, cross-correlation and numerical modeling. From the modeling the 2D model, 3D model and different scenarios with particle transport is discussed.

5.1. Statistical analyses

5.1.1. Correlation

5.1.1.1. Upper and lower aquifer

The high correlation is indicating that the heads in the upper and lower aquifers is following the same trend, and has the same reaction pattern to hydraulic parameters such as the river flow changes (fig. 28) The high correlation is indicating he heads in the upper and lower aquifers is following the same trend, and has the same reaction pattern to hydraulic parameters such as the river flow changes and the recharge variations. A high correlation together with a decrease in pressure difference between the upper and lower aquifer, is indicating a really thin or not existing organic layer at this point.

The 3 other wells, 12, 11 and 15, similar correlation, all above 0.5. This means that there is a good correlation. The upper and lower aquifer is reacting similar to the different parameters. In these areas the lower aquifer is not reacting as fast to the changes within the aquifer as the upper aquifer like in the area of well 9.

5.1.1.2. Hjartsjå Lake

The correlation between Hjartsjå Lake and the precipitation is low, 0.23, this means that the precipitation does not have significant impact on the level of Hjartsjå Lake (fig. 29).

The correlation between the upper aquifer and the lake is showing a wide specter of correlation (fig. 30). Well 15, which is closest to the lake is correlating well with the lake, 0,71. An increase in the level of the lake leads to an increase in the head of the upper aquifer at well 15. Well 12a is having the lowest correlation with the lake at 0,28. This means that a change in the lake does not have an effect on the head in the upper aquifer at well 12a. While the upper aquifer at well

9 and 12 are showing low correlation with the lake, well 11 is showing a correlation of 0.54. The correlation in well 11 and 15, which is placed in the north end (11) and the south end (15) of the aquifers, shows that there is a connection between the upper aquifer and the lake, and it is indicating a positive connection. The correlation of 0.37 in well 9a is most likely because of the distance to the lake.

The correlation between the upper aquifer and the lake is much higher than the correlation between the lower aquifer and the lake (fig. 31). All the wells in the lower aquifer are not showing correlation to the r. This indicate no connection, or a weak connection. This indicate a negative connection between the lower aquifer and the lake. The low or non-existing connection between the lake and the lower aquifer means that the organic layer most likely continues underneath the lake.

The correlation between the lake and the flow from the power plant is low, which means that the release of water from the power plant does not have big influence on the lake level.

5.1.1.3. River

The correlation between the upper aquifer and the river is high for all the wells (from 0.9 to 0.68) (fig. 32). The river is influencing the head of the upper aquifer. The correlation between the lower aquifer and river is also giving a correlation, but not as high correlation as the upper aquifer (0.85 to 0.47) . This means that there must be a connection between the river and the lower aquifer. The correlation is highest in well 9b, 0, 86, which is indicating that the organic layer is not reaching beyond well 9. Well 11, 12 and 15 is also showing a correlation (0.51, 0,47 and 0.68) this means that there is a connection between the river and the lower aquifer. The connection might indicate that the organic layer along the river is thin and the water manage to percolate through, or the river infiltrates at thinner parts of the organic layer.

5.1.2. Cross-correlation

5.1.2.1. Upper- and lower aquifer

The results of the cross correlation between upper and lower aquifer at well 9 gives no lag between the upper and lower aquifer (fig. 33). This means that the Pb9b, which is the output, does not have any lag to Pb9a, which is the input. This implies that the upper and lower aquifer at well 9 are synchronized when changes in heads occur.

The correlogram of the upper- and lower aquifer show that there is no lag between the upper and lower aquifer. This implies that the upper and lower aquifer have the best correlation at 0 lag. The gradually decrease in correlation with the increase in lag~~s~~ indicates a connection between the upper and lower aquifer (fig. 33).

Hjartsjå Lake and the recharge does not show any lag (fig. 34)

Looking at the cross correlation between the rivers influence on the upper aquifer at well 9 (fig. 36) is there a clear peak at lag -1. This means that the river is feeding the upper aquifer (Lee and Lee, 1999). It is also indicating a clear correlation between the river and the upper aquifer, where the lag is one day. The lower aquifer at well 9 (fig. 35) is showing a lot of the same tendencies as the upper aquifer and the river. There is one-day lag, and the correlation is not as high as the upper aquifer, but still the river has a great impact on the lower aquifer.

The correlation between the lake and the power plant (fig 36), is showing a higher correlation over all the lags then the recharge. However, the lack of a peak and the flat structure of the point indicates a low correlation. This means that the power plant does not have a big impact on the lake level.

The cross correlation between the flow from the power plant and the upper aquifer at well 11 (fig. 36) is partly showing a negative correlation. This means that there has been an increase in the flow from the power plant and a decrease in the heads in the upper aquifer (StataCorpLP, 2013). However, in general the correlogram is indicating that the power plant has little effect on the heads in the upper aquifer. The power plant and the lower aquifer (fig. 36) are also showing a negative correlation, meaning an increase in flow from the power plant leads to a decrease in heads of the lower aquifer. There is somehow a decrease in the correlation at both sides from lag -1, but it is not a distinct peak. In general, the flow in the power plant has a low effect on the lower aquifer in.

5.2. The organic layer

From the sediment cores (described in ch. 2), is it a reoccurring layer of organic matter in all the cores. This organic layer have big variations in thickness, but the general trend is that it is getting thinner westward. This layer of organic matter is most likely the layer dividing the groundwater system into two aquifers. By studying the pressure heads from the wells (fig… ch.2) is it clearly showing a pressure difference of approximately 1,5 meters between the upper and lower aquifer. This pressure difference support the case of having two different aquifers. The pressure head of the lower aquifer is at several wells above ground, indicating an artesian pressure in the lower aquifer. This leads to the interpretation that the organic layer is impermeable or with very low permeability. There is no pressure difference between the upper and the lower aquifer at well nine, which indicates that the organic layer is thinning towards well nine, and this is interpreted as a result of the organic layer disappearing. The sediment logs is also showing that the organic layer is continuing in northeast direction towards the valley side, and the organic layer is also appearing by the tunnel opening. Because of the negative boarder between the lake and the lower aquifer, the lower aquifer is most likely continuing underneath the lake. In the westward direction data from well nine is the only indication that the organic layer is disappearing. The extent of the organic layer in westward direction is therefore not fully understood. The extent of the organic layer, based on the sediment logs and the wells, is represented in (fig. 52).

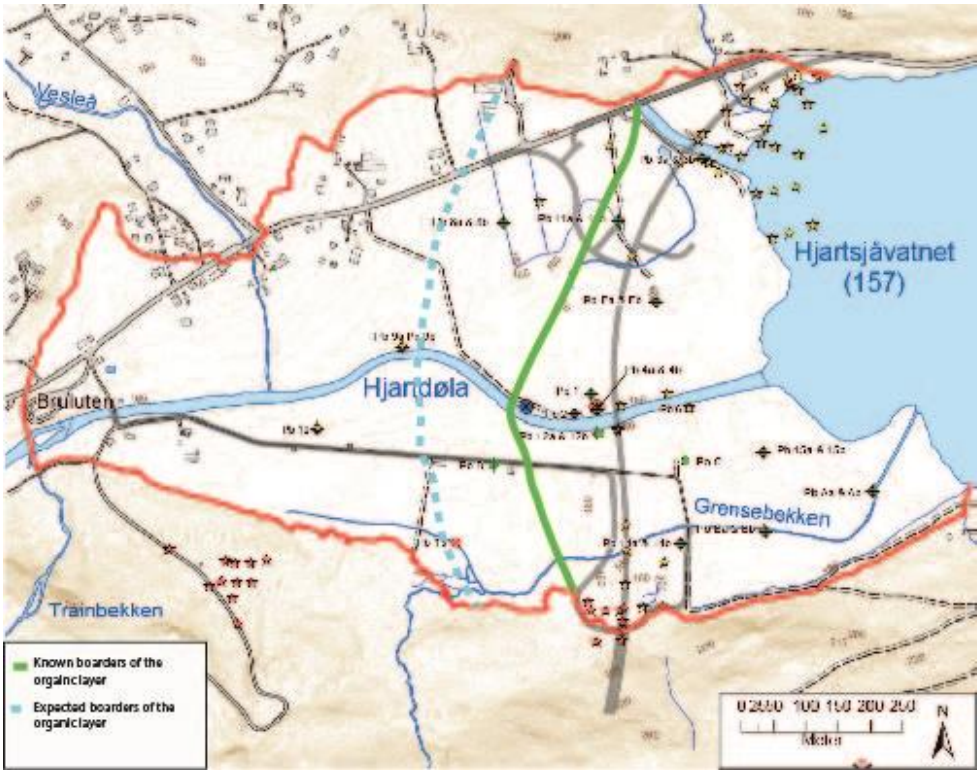


Figure 52: The area west of the green line is proven by sediment cores, and pressure diffrence to have an organic layer true the sediment logs and the pressure heads from the wells. The blue stippled line is representing where the organic layer most likely is disappearing.

5.3. Numerical modeling

5.3.1. 2D Model

The 2D model was indicating that the length of the organic layer does lead to a change in groundwater table (fig. 19). Since the extent of the organic layer only is based on the measurements from upper and lower aquifer in well 9, this assumption has an impact on the flow of the groundwater. The extent of the organic layer also affect the recharge of the lower aquifer. Looking at the correlation between the lower aquifer and well nine (fig. 5), well nine is showing the highest correlation in the lower aquifer. The river is recharging the lower aquifer, meaning the length of the organic layer impacts the recharge in the lower aquifer. The flow in between the upper and lower aquifer is also a crucial part affected of the length of the organic layer.

Studying the impact of the depth of the lower aquifer (fig. 20) this will not affect the dynamics of the aquifer at all. This could be explained by the difference in thickness of the upper and lower aquifer. Even though the lower aquifer is 25 meters or 50 meters is it still a deep aquifer meaning changes need to be big to have an impact. The size of the lower aquifer is still deep compared to the upper aquifer, even though the depth is 10 or 20 meters deeper. This means that the unknown depth of the aquifer most likely does not have a big impact on the model.

5.3.2. 3D Model

From the input parameters (table 2) in the model, constant head (west boarder) in the west end of the aquifer, the general head, and the drain is unknown factor. According to the flow budget (fig. 22) is general head the parameter providing most water into the aquifer, and constant head is having the highest discharge. This means these two parameters have the biggest impact on the model. For the constant head is it possible to extract an approximately groundwater head used as a range, from well nine, and upper aquifer in well E. The connection between the lower aquifer and the west part of the model is not known. Based on the estimation that the sediments is poorly to medium sorted as the sediment cores are showing and that the hydraulic conductivity is more or less the same. This leads to the same constant head in both the aquifers, and all the three layers in the aquifer.

The general head is unknown and only fitted by calibration. The connection between the layers when meeting the bedrock is also unknown. For the calibration only wells in the east end was used, since there is lack of wells in the west end. More wells in the west part would have given a better model, but in this case the east part by the road and the drinking water wells is the most essential part.

The geometry of the model was made by having the same constant depth of 50 meters. The bottom layer has the same topography as the top layer. The reason for this was that the bottom geometry is unknown. The bedrock might go steep down into the sediments, or gentle slopes making the sides of the aquifer shallow. The topography is most likely not the same at the bottom of the lower aquifer as on the top of the upper aquifer. Since the bedrock “topography” is unknown, the top topography was used. However, the bedrock “topography” might have a steeper gradient towards west than the valley plain. This could have quite a big impact on the model, and be one reason why it was hard calibrating the model. Even though the depth of the lower aquifer was indicating small impact on the model, if the sides have gentle slopes this might lead to the lower aquifer getting smaller. The connection between the upper and lower aquifer with the steep mountainside in the south is not known.

The model had some problems with flooded areas. However, the flooding was only by a few centimeters. This is most likely due to the interpolation of the layers. The layers was created by interpolating a scatter point, this means that the topography is a continuation of the two former points. The lead to depression in the topography at places where there was not any depression. Comparing the topographical map of the model, with a real topographical map showed that these flooding was not a case with the real topography. Trying to put several points led to problems in the organic layer. Since the organic layer is thin, this easily ended up with the bottom layer of the organic layer above top layer of the organic layer. Since the flooding only was a few centimeters, and the topography was higher than the flooding, it would not have any impact on the results of the model.

Higher hydraulic conductivity was found around well 1 and 2 (table 1), in the same area as the old drinking well. Due to this change from 38 m/d day in hydraulic conductivity to 0,3 m/d at well E, particle transport was used in this area in order to see if a potential accident with a truck would lead to danger for the drinking water well. Even though the spill was on top of the area with lower hydraulic conductivity, the particles did not penetrate true the organic layer (fig 51). Only when the vertical hydraulic conductivity was set to 60 m/d, the particles penetrated into the organic layer but not through it entering the lower aquifer. 60 m/d in vertical hydraulic conductivity is not likely, it was only done to see what changes was needed for a spill to reach the lower aquifer. If the spill was at the south side of the river, all the particles went into the river. The river and the lower aquifer has a correlation coefficient around 0.5 in the area around the drinking water well. This means that there might be a change of the particles entering the lower aquifer. Since the drinking water wells is upstream from the road, and all the particles entering the river will enter the river downstream of the drinking well, the spill will most likely not polluted the water for the drinking wells. Whit a spill will the pollution enter the lake, however there is no risk of polluting the lower aquifer since there is a negative boarder between the lake and lower aquifer.

5.4. Further work

There is still many unknown parameters about the lower aquifer and the surrounding aquifer. In general more information of the organic layer would make a better understanding of the aquifer. More sediment cores would be useful for mapping the extraction of the organic layer, with sediment cores it would also be possible calculating more hydraulic conductivity. The range of the hydraulic conductivity, there is a big variation in hydraulic conductivity in the aquifer. Another well in the west end would be useful for better identify the connection with the lower aquifer, and the constant head. More measurements of the river, where the elevation of the diver/ river bottom elevation is known. Then the next step would be to try making a transition model.

6. Conclusion

- Well 9 has the highest correlation of all the wells. Based on the correlation of 0.9 in well 9 is there a high interaction between the upper- and lower aquifer at this area.
- Based on the correlation between upper- and lower aquifer is there a positive boarder between the upper aquifer and the lake, and a negative boarder between the lower aquifer and the lake.
- From the outcome of this study is there a good correlation between the river and upper- and lower aquifer.
- The hydrogeological system is showing no seasonal lag or time lag based on the statistical analyses of this thesis.
- There is an organic layer dividing the upper and lower aquifer. This organic layer is most likely an impermeable layer, or with low permeability.
- Based on the 2D model the length of the organic layer have an impact on the heads in the upper- and lower aquifer.
- Based on the model produced in this thesis, an accident along the road will not pollute the drinking water wells.

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